BBC

FROM THE MAKERS OF ***BBC SCIENCE FOCUS*** MAGAZINE

THE THEORY OF *(nearly)* EVERYTHING

The big ideas and discoveries in science explained

THE SPEED OF LIGHT
THE ORIGIN OF LIFE
THE NATURE OF GRAVITY
THE FUTURE OF GENETICS
THE STORY OF THE UNIVERSE
THE COMPOSITION OF STARS
THE HISTORY OF BRAIN RESEARCH
THE EXISTENCE OF BLACK HOLES
UNDERSTANDING QUANTUM PHYSICS
BREAKTHROUGHS IN SYNTHETIC BIOLOGY
THE STRUCTURE OF THE PERIODIC TABLE
THE COMPOSITION OF HUMAN CELLS
THE STRUCTURE OF THE ATOM
THE SEARCH FOR DARK MATTER
THE THEORY OF EVOLUTION
THE END OF THE UNIVERSE
THE STRUCTURE OF DNA
THE SPEED OF LIGHT
THE ORIGIN OF LIFE
THE NATURE OF GRAVITY

Two simple questions

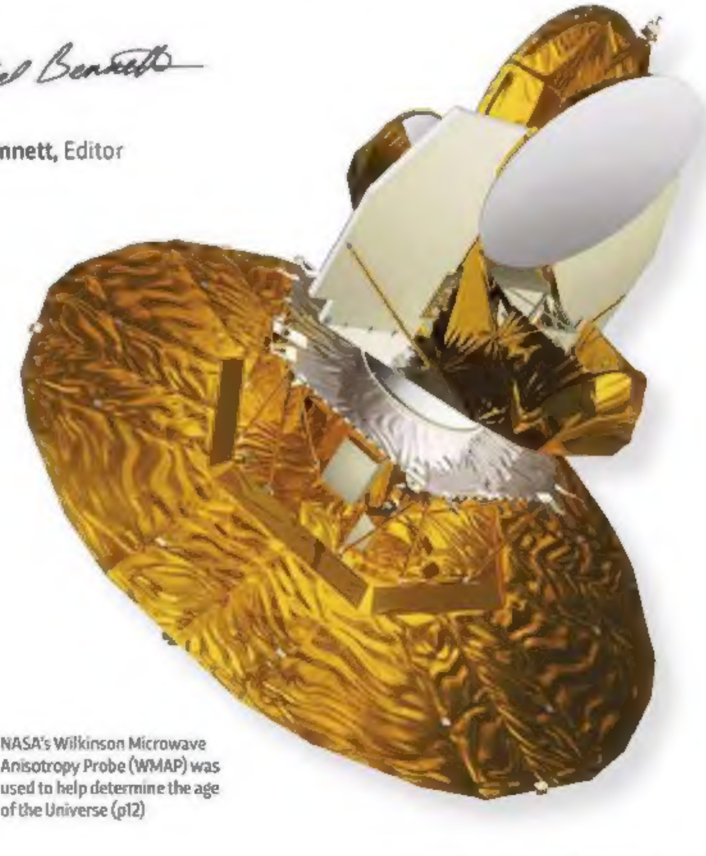
Humans are curious animals. Curious in terms of our behaviour, certainly but more importantly, we're curious by nature. We have a deep-seated need to discover new things and understand why the things we discover are the way they are. It's this curiosity that brought us down from the trees and led us up into space, and at the heart of it are two simple questions. Questions that, despite the best attempts of our brightest minds, we still can't quite answer. Where did we come from? And where are we going? Science has brought us closer than anything else to getting viable, and verifiable, answers to those questions. But we're still a long way from having the full story and so the search for answers continues.

That search is not in vain, though. Looking for answers to these questions has enabled us to accumulate a vast body of knowledge that gives us a very good idea of how the Universe began, how stars and planets form, how physical traits are passed from parents to their offspring, and how our brains work. And although this knowledge may not yet be able to answer those two simple questions, it's enough to give us an inkling of what the answers might be and where we might find them.

That's where this Special Edition comes in. We've sought out the experts who are searching for the answers to those questions and asked them to explain how we've arrived at our current understanding of the Universe and ourselves, and what implications that understanding has for the future... of science and us. Because, while we may not have all the answers yet, there's no question that the knowledge we've accumulated already is invaluable.

Daniel Bennett

Daniel Bennett, Editor



NASA's Wilkinson Microwave Anisotropy Probe (WMAP) was used to help determine the age of the Universe (p12)

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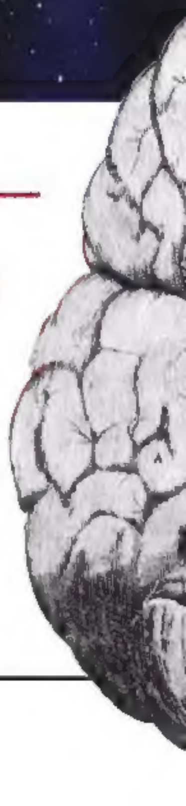
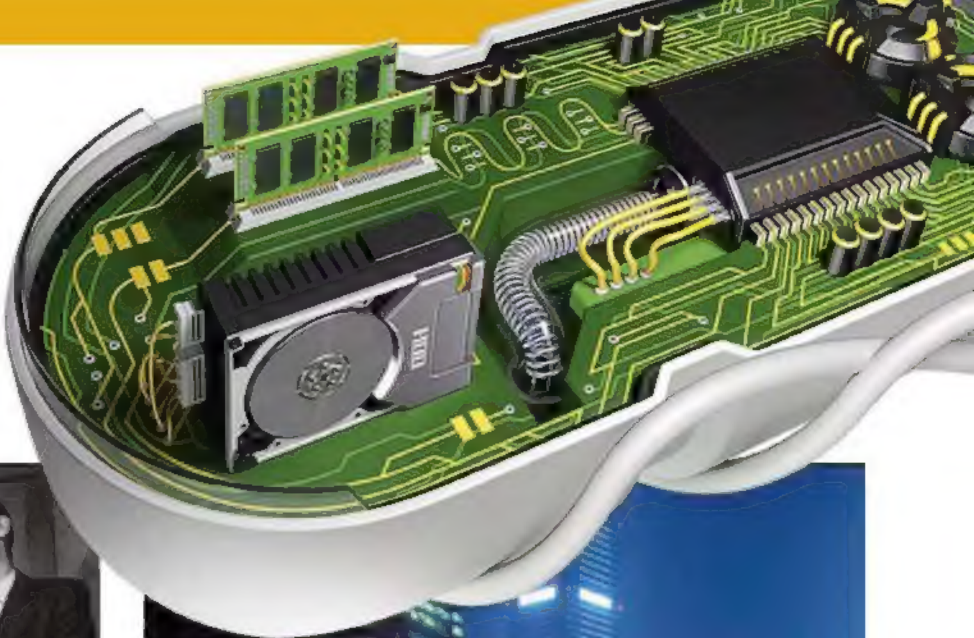
THE FUNDAMENTALS OF PHYSICS

THE FUNDAMENTALS OF LIFE

THE NEXT BIG STEPS FOR SCIENCE





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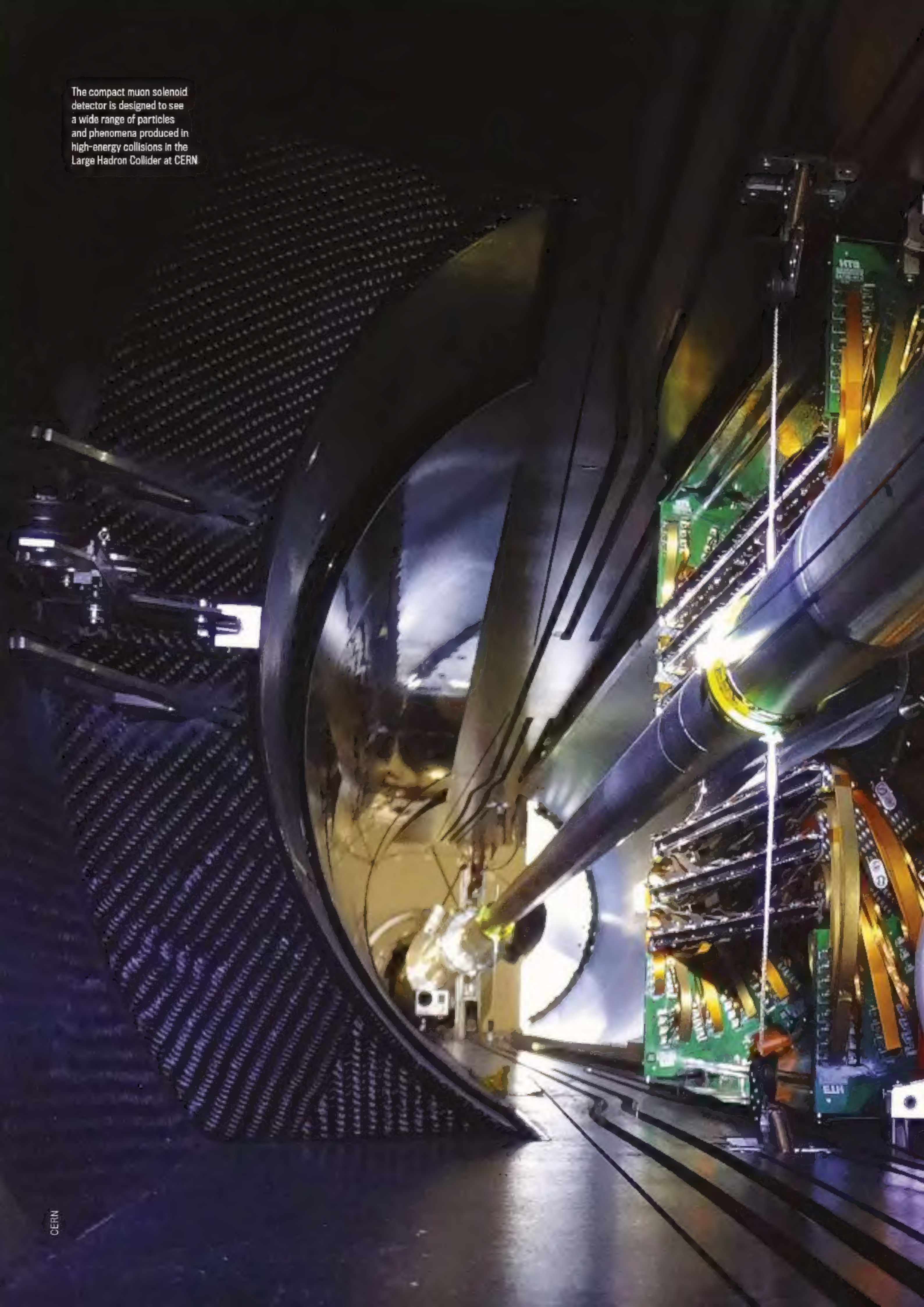
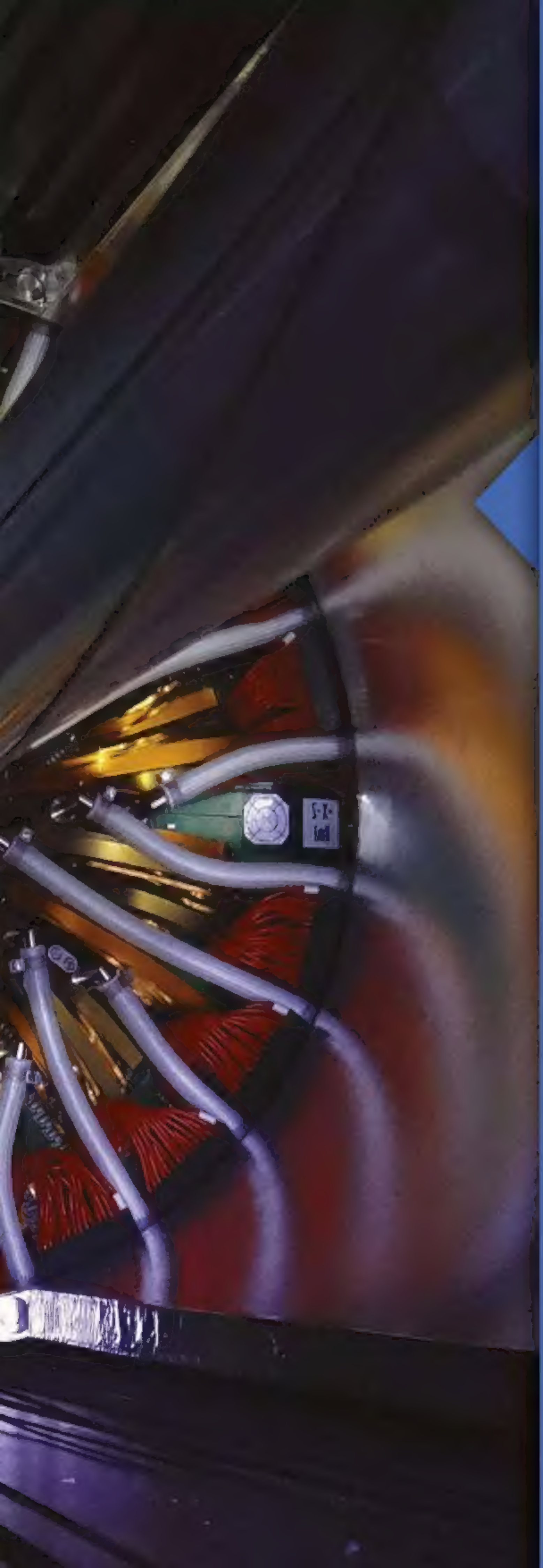


The compact muon solenoid detector is designed to see a wide range of particles and phenomena produced in high-energy collisions in the Large Hadron Collider at CERN

CERN



THE FUNDAMENTALS OF PHYSICS

THE STORY OF THE UNIVERSE

From the Big Bang to the formation of the Solar System, *Dr Stuart Clark* and *Dr Elizabeth Pearson* reveal the birth of the Universe and the history of its life in six chapters

The year 2009 could go down in the astronomical textbooks as the one when a revolution in our understanding of the Universe began. The protagonist at the centre of this upheaval was not a person but a machine: a space probe called Planck. Named after the great German physicist Max Planck, the spacecraft was launched by the European Space Agency that year and was tasked with detecting the 'blueprint' of the Universe – capturing a snapshot of the seeds of the stars and galaxies that surround us today.

Prior to its launch, cosmologists had spent over a century constructing mathematical theories to describe the story of the Universe, from the earliest moments to the present day. But analysis of the data returned by Planck has revealed a number of plot holes – or 'anomalies' as the scientists call them – that don't seem to fit the story.

For one thing, data from Planck indicates that the Universe is older than expected by about 50 million years. The Universe also contains more of the mysterious dark matter and fewer atoms than previously thought. And while these two things may sound serious, in reality they are the least of a cosmologist's worries.

Much more troubling is the so-called 'cold spot' in the radiation from the early Universe that Planck has recorded – a region that looks significantly colder than current theories allow. Indeed, the temperature pattern across the whole Universe looks strangely lopsided.

Discoveries such as these are shedding new light on the history of the Universe and revealing more of the story of how we arrived at the cosmos we see around us today.

The Large Hadron Collider is used to recreate conditions in the moments immediately after the Big Bang

CHAPTER 1: **THE BIG BANG**

The very moment of the Big Bang remains shrouded in as much mystery as ever. It's the point at which the Universe began – space and time were formed and all the matter and energy that we see around us somehow came into existence. Data from the Planck space probe indicates this happened 13.82 billion years ago. Initially, there were no stars or galaxies, just a hot, dense sea of particles and radiation.

Immediately after the Big Bang, space began to expand, spreading out matter and energy. The trouble is the theory that we use to understand the expansion, Einstein's Theory of General Relativity, doesn't work at the extreme densities of the Big Bang, so we are searching for a way to extend it.

The best template is quantum theory, which deals with the physics of the very small and provides a basis for all the forces of nature, except gravity. To investigate such a theory, scientists must turn to the Large Hadron Collider (LHC) at CERN in Switzerland, which recreates the conditions thought to have been present in the Universe a fraction of a second after the Big Bang.

"The LHC gives us a mini-Universe in the laboratory," says Dr Anupam Mazumdar, a cosmologist at the University of Groningen.

The Big Bang saw the Universe rapidly expand out of a single, incredibly dense spot. The heat from its 'birth' is still detectable today, almost 14 billion years later

IN A NUTSHELL

How the Universe began was one of the biggest questions facing science. Over the course of the 20th century, a series of astronomical observations and fortuitous physics experiments finally verified the Big Bang theory.

The fundamental elements of the Universe burst out from the Big Bang (bottom). As they spread, and cooled, they gradually coalesced to form the planets and galaxies we know today

SCIENCE PHOTO LIBRARY

While the experiments involving the LHC can show what particles were prevalent in the primordial Universe, theoreticians then have to form a theory to understand them.

String theory is a possible quantum theory of gravity, but it is unclear whether it bears any resemblance to reality, because the mathematics are currently unable to predict anything that can be tested in a lab or observed. For now, the moment of the Big Bang remains *terra incognita*.

CHAPTER 2: **INFLATION**

10-35 seconds after the Big Bang

Until the Planck probe, almost every observation of the Universe's largest scales had suggested that it is almost uniform. Sure, there are clusters of galaxies and huge voids, but even these are comparatively small when the Universe is considered as a whole.

As a result, cosmologists had developed a mathematical framework called inflation to explain the uniformity. First proposed in 1980 by Alan Guth, a particle physicist from the Massachusetts Institute of Technology, it postulated that, right after the Big Bang, a period of extraordinary expansion took place. In the blink of an eye, the Universe grew by a factor of at least 1,060. This would smooth out any large-scale deviation across the Universe, making it appear uniform. Only the smallest fluctuations in the density of matter and energy would remain, the cosmologists theorised. Remarkably, these fluctuations were found in 1989 by NASA's Cosmic Background Explorer (COBE) satellite and they amount to no more than one part in 100,000. They are the seeds from which the galaxies have grown.

The Planck probe measured these fluctuations in greater detail. It split the sky into an image made up of a billion pixels and observed each one a thousand times during its three-year mission. This produced a map of the sea of microwaves that bathe space – the cosmic microwave background (CMB) – unlike anything that had been seen before.

It's these subtle fluctuations in this radiation left over from the Big Bang that provide astronomers with their blueprint of the early Universe – the distribution of matter and energy a fraction of a second after the Big Bang. As soon as the data from Planck was released, problems appeared that the cosmological community are still attempting to solve.

For example, there is a suspiciously large cold spot, which suggests that a vast clump of matter was present in the early Universe and it's much denser than inflation can explain. More troubling is that one side of the Universe has fluctuations that appear stronger than the other, indicating an uneven distribution of matter across the expanse of space.

"This is very strange," says Dr George Efstathiou, Professor of Astrophysics at the University of Cambridge and a member of the Planck science team. "I think that if there really is anything to this, you have to question how that fits in with inflation. It's really puzzling."

But it may not spell the end for the theory of inflation just yet. "My gut instinct is that these anomalies point to a more specific model of inflation," says Dr Rose Lerner, a cosmologist at the University of Helsinki in Finland, who works independently of the Planck consortium.

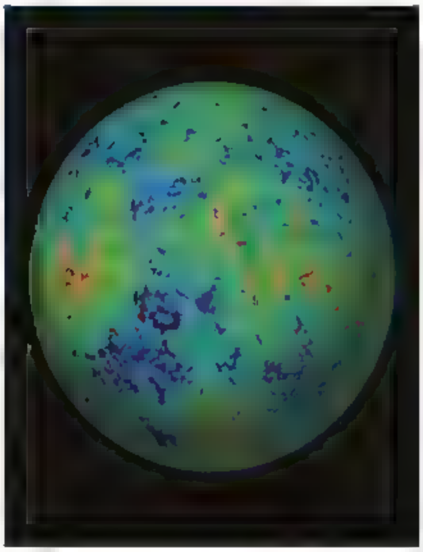
Another solution to the anomalies, according to Prof Matthew Kleban of New York University, is that during the sudden expansion that happened during inflation, our Universe slammed into a neighbouring one. This sent shockwaves rippling through our cosmos that imprinted the anomalies we see today. If so, we should think of them as a cosmic bruise. Testing such a controversial idea, however, is very tricky.

CHAPTER 3 **PARTICLE CREATION**

1 minute after the Big Bang

At one minute old, the entire Universe resembled the interior of a star – but on a vast scale. Particles that would become the nuclei of all the atoms in the Universe were built in this cauldron. Mostly these were single protons that would become hydrogen, but around a quarter of the particles transformed into helium nuclei, containing two protons and two neutrons. Trace amounts of lithium and beryllium were also produced.

The evidence for all of this furious activity is all around us today in the chemical make-up of the Universe. We know from measurements of the radiation given off by our Sun and other stars that 98 per cent of the ►



A map of the Cosmic Microwave Background – the afterglow radiation of the Big Bang

THE KEY EXPERIMENT

A baffling find by Arno Penzias and Robert Wilson that the Universe was warmer than it should be earned them a Nobel Prize

Robert Wilson (left) and Arno Penzias (right) in front of the antenna that fortuitously picked up the heat signature of the Cosmic Microwave Background

The Horn Antenna at Crawford Hill in New Jersey was built for use with satellites, so the shape of it was designed to minimise interference from the ground and provide the best possible measurement of the strength of radio noise from the sky.

The nature of this radiation depends on the temperature of the radiating object. The amplifiers used in the receiver were cooled to 4.2 Kelvin (-268.8°C) using liquid helium, and Penzias devised a 'cold load', cooled by liquid helium to about 5 Kelvin, which was used to calibrate the system.

By switching the antenna from observations of the cold load to observations of the sky, they could measure the apparent temperature of the Universe (expected to be 0 Kelvin), then subtract out known factors, such as the interference from the atmosphere above. But in 1964 it soon became clear that the radiation coming from the antenna into the receiver was at least 2 Kelvin hotter than they could explain. The pair did everything they could think of to remove any sources of interference, including cleaning out the layer of droppings that had accumulated in the antenna horn from a pair of nesting pigeons. Nothing made much difference. The mystery of the 'excess antenna temperature' continued to baffle them throughout 1964.

That is until the pair realised, with the help of Robert Dicke, James Peebles, Peter Roll and Dave Wilkinson at Princeton, that what they were looking at was the afterglow radiation from the Big Bang.

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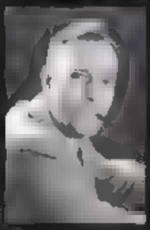
TIMELINE

1929



Edwin Hubble discovers the distance of a galaxy from us is directly proportional to the velocity implied by its redshift. Georges Lemaître had published this in 1927, but nobody had noticed.

1931

Lemaître writes: "We could conceive the beginning of the Universe in the form of a unique atom, the atomic weight of which is the total mass of the Universe."

1948

Ralph Alpher (left) and Robert Herman calculate that the leftover radiation from the primeval fireball should still fill the Universe today, with a temperature of about 5 Kelvin (-268°C).

1964

Arno Penzias and Robert Wilson discover a weak hiss of radio noise coming from all directions in space. The following year, this is explained as the leftover radiation from the Big Bang.

1989

Launch of the Cosmic Background Explorer satellite (COBE), which detected tiny irregularities (ripples) in the background radiation, confirming the accuracy of the Big Bang model.

2001

The Wilkinson Microwave Anisotropy Probe (WMAP) launches, making precision measurements that pin the age of the Universe down as 13.8 billion years.

Universe remains in the form of this primordial hydrogen and helium. Only two per cent of the original atoms have been processed into heavier chemical elements while inside stars.

CHAPTER 4 **THE DECOUPLING OF MATTER AND ENERGY**

380,000 years after the Big Bang

This is the moment when the radiation detected by the Planck probe was released into space. Until then, the Universe had been a searing mass of atomic nuclei, lighter particles and energy. It had been impossible for whole atoms to form; whenever a nucleus and an electron particle bonded together, the torrent of radiation smashed them apart again.

Now, the continual expansion of space had weakened the radiation so much that it could no longer break apart the atoms. This was a watershed moment because, with most of the previously free particles now confined into atoms, it was as though the fog cleared.

In the same way that we are able to see to the horizon on Earth on a clear day, the Planck probe enabled us to see this radiation, which has spent in the region of 14 billion years travelling across space while preserving a record of the density of the various clumps of matter that became galaxies. It's this record that now provides troubling insights into the previous inflation.

CHAPTER 5 **THE COSMIC DARK AGES**

1 million years after the Big Bang

Initially, the decoupled radiation would have been visible to the human eye – not that there were any humans around to see it. But the continued expansion of space stretched the radiation into the infrared and then the microwave sections of the electromagnetic spectrum.

The Universe became dark.

Even after a million years, there were no celestial objects, so no sources of light. These were the Cosmic Dark Ages. Slowly, the sea of atoms spread across the Universe began to form into clumps, pulling themselves together to become the first celestial objects. This was driven by the gravity of 'dark matter' clouds composed of particles that formed shortly after inflation.

The Cosmic Dark Ages ended with the first celestial objects. The first stars were purely hydrogen and helium, and some could have been thousands of times the mass of the Sun. They lived for just hundreds of thousands of years before destroying themselves and seeding the Universe with the heavier elements needed to form planets and life.

In March 2013, the Hubble Space Telescope pinpointed one of the Universe's oldest stars right on our celestial doorstep, 'just' 190 light-years away. Known as the Methuselah star, it has an estimated age of 14.5 billion years – give or take 0.8 billion years. It's only this margin of error that means it's potentially consistent with the supposed age of the Universe. This might make it seem as if the star is older than the predicted age of the Universe, but it's more of a quirk of how accurately we're able to measure the age of a star.

The first black holes were those found at the centres of galaxies. Although a black hole emits no light, matter falling into its gravitational clutches does heat up and emit radiation. They would have ended the Cosmic Dark Ages as surely as the first stars.

The first galaxies – known as quasars – were voracious monsters. Their feeding black holes gave out as much light as their collections of stars. Gradually, the black holes consumed all the matter in their vicinity, leaving only the stars to shine within the galaxy.

CHAPTER 6 **THE FORMATION OF THE SOLAR SYSTEM**

8.8 billion years after the Big Bang

The Solar System started out as a huge cloud of gas (hydrogen and helium), which collapsed and rushed towards the centre of the mass, fusing together until it burst into life as the star that we now know as the Sun.

As the Sun was forming, so were the planets. Before our star was born,

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The light from Pandora's Cluster – a group of galaxies in the deepest realms of the observable Universe – has been shifted to the red end of the spectrum due to the expansion of the Universe

NASA

> "Planetesimals were the building blocks of the Solar System. After a few million years of crashing together, these bodies began to resemble the planets"

another larger one had died in a supernova, filling the cloud with gas and dust. This debris gradually formed a protoplanetary disc – a huge, flat circle made up of hundreds of lumps of rock and ice called planetesimals.

These planetesimals were the building blocks of the Solar System. After a few million years of crashing and melding together, these bodies began to resemble the planets as we know them today.

Close to the Sun, temperatures were too high for volatile chemicals, such as water, to remain solid in any quantity. The initial protoplanetary disc contained only a small amount of rocky solid material, so the four planets that formed closest to the Sun were comparatively small. But, 600 million kilometres from Earth, at what is now the outer edge of the asteroid belt, temperatures were cool enough for gases to form thick atmospheres around rocky cores, creating the gas giants – Jupiter, Saturn, Uranus and Neptune.

It wasn't just planets forming, though; several moons did, too. Many moons are former planetesimals captured by a planet, but a few had a much more violent beginning. When the infant Earth collided with another young planet, a huge plume of debris was trailed behind. After a few hundred million years, it melded together to create the Moon.

By four billion years ago, the planets and moons had formed, but the Solar System still looked very different from its current state. There were probably many more planets than the eight

NEED TO KNOW

COSMOLOGICAL REDSHIFT

HUBBLE'S LAW

MICROWAVES

Left to right: the Sun, Mercury, Venus, Earth, Mars, Jupiter, Saturn (not to scale)

"When comets crashed into the surface of the early planets, water didn't boil off immediately but instead formed vast oceans"

we know today and they would have been much closer together.

Over time, the outer planets began to move slowly away from the Sun, throwing the gravitational forces of the Solar System off balance. This caused several early planets to be thrown into deep space and, around four billion years ago, the remaining debris was pelted against the planets.

This period, now known as the Late Heavy Bombardment, left scars that can still be seen on the faces of the Moon, Mars and other rocky planets. On Earth, such craters have been hidden by the actions of volcanism or worn away by the atmosphere.

The most significant relic left on our planet from that bombardment is the array of elements left behind. During Earth's formation, metals such as gold and copper sank to the core, so the deposits we find in the crust today must have arrived on asteroids and comets at a later date.

Perhaps the most important delivery to Earth was water. The early Solar System was too hot for water to settle but, by the time of the Late Heavy Bombardment, temperatures had dropped. When comets crashed into the surface of the early planets, water didn't boil off immediately but instead formed vast oceans.

After hundreds of millions of years, the planets had settled into their orbits and began to grow. Volcanism shaped their surfaces while, deep inside, their molten cores began to cool. The cores of the smaller terrestrial planets solidified; without the flow of metallic cores, their protective magnetic fields faded, leaving their atmospheres unshielded from solar winds. As time progressed, such differences between each world became exaggerated, leading to the variation in planets that we see in the Solar System today. **SF**

by **DR STUART CLARK** @DrStuClark
Dr Clark is an author, cosmology consultant for the European Space Agency and a Fellow of the Royal Astronomical Society

and **DR ELIZABETH PEARSON**
Dr Pearson is the news editor of BBC Sky at Night Magazine

STOCK

THE COMPOSITION OF STARS

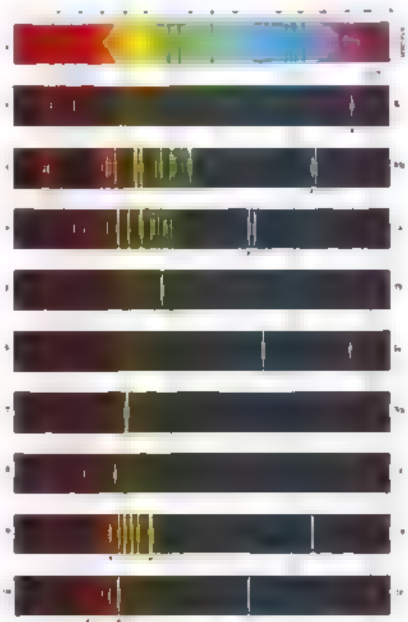
Unlocking the meaning of features in the spectrum of sunlight enabled us to identify elements present in stars. *Dr John Gribbin* explains how it also gave rise to a new science – astrophysics

The philosopher Auguste Comte wrote, in 1835, that "there is no conceivable means by which we shall one day determine the chemical composition of the stars". So much for philosophy. By the time Comte died in 1857, astrophysicists were well on the way to finding out what stars are made of. Indeed, spectroscopy, the tool they would use to do it, had already been invented decades before Comte made his pronouncement.

In 1802, the British scientist William Hyde Wollaston was studying sunlight by passing it through a slit to make a narrow beam and then through a glass prism to spread the beam into a solar spectrum. By doing so, he noticed that the colours were separated by dark bands – two in the red part of the spectrum, three in the green and two in the blue-violet region.

Wollaston thought these were simply gaps between the colours, but his discovery triggered the interest of the German Joseph von Fraunhofer, who was able to produce much more detailed spectra in the second decade of the 19th century. Eventually, he identified 574 separate lines. Today, all the dark lines in the solar spectrum (even more than he counted) are known as Fraunhofer Lines. A clue to their origin emerged in the same decade that Comte died, the 1850s.

It started with the work of Robert Bunsen and Gustav Kirchhoff in Germany. This is the same Bunsen whose name is known to everyone who takes chemistry at school, thanks to the famous burner. Early in the 1850s, the city of Heidelberg had pipes installed. These would distribute inflammable gas derived from coal to households and businesses – and to the scientific laboratories of the university. It was the inspiration for Bunsen's work with the burner that now bears his name. The burner combines oxygen and inflammable gas in a controlled way, producing a clear flame. It's an ideal tool for a chemical test in which substances are identified by the colour they give to a flame.



Robert Bunsen and Gustav Kirchhoff found patterns of bright lines in the spectra of heated elements

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All in the detail

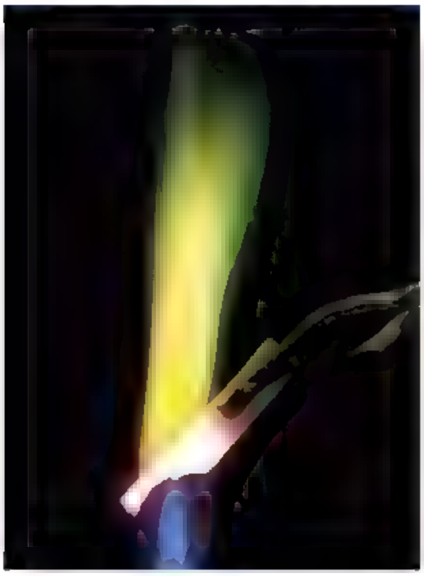
Bunsen originally used coloured filters to calibrate these tests, but Kirchhoff pointed out that it would be possible to make a more detailed analysis. Together, they built an apparatus that included a narrow slit for the light to pass through, a collimator to narrow the beam and a prism to spread the light into a rainbow. Finally, an eyepiece, like that of a microscope, allowed them to view the spectrum. This was the first time all these components had been assembled into a single instrument – a spectroscope – although Fraunhofer had previously used a prism and eyepiece combination in his work.

Bunsen and Kirchhoff knew that when different substances were put in the clear flame of a burner, they burned with different colours. A trace of sodium, for example, turns the flame yellow, while copper colours the flame green/blue. When they analysed the light from these flames using

IN A NUTSHELL

A ground-breaking experiment studying the spectrum of light revealed the first signs of elements making up the Sun. Later, a scientific pioneer found that every star in the Universe consists almost entirely of just two elements.

The Pleiades star cluster, also known as the Seven Sisters. Thanks to spectroscopy, we can identify the elements it's made from...



Copper being burnt in a flame from a Bunsen burner. Copper burns with a green/blue flame in the presence of oxygen to form copper (II) oxide

spectroscopy, they found that each element produced bright lines in the spectrum at precise wavelengths. The lines occurred in the yellow part of the spectrum for sodium, in the green/blue part of the spectrum for copper, and so on. One evening, from their laboratory in Heidelberg, Bunsen and Kirchhoff were able to analyse the light from a major fire in Mannheim, some 16km away and identify lines produced by the presence of strontium and barium in the blaze.

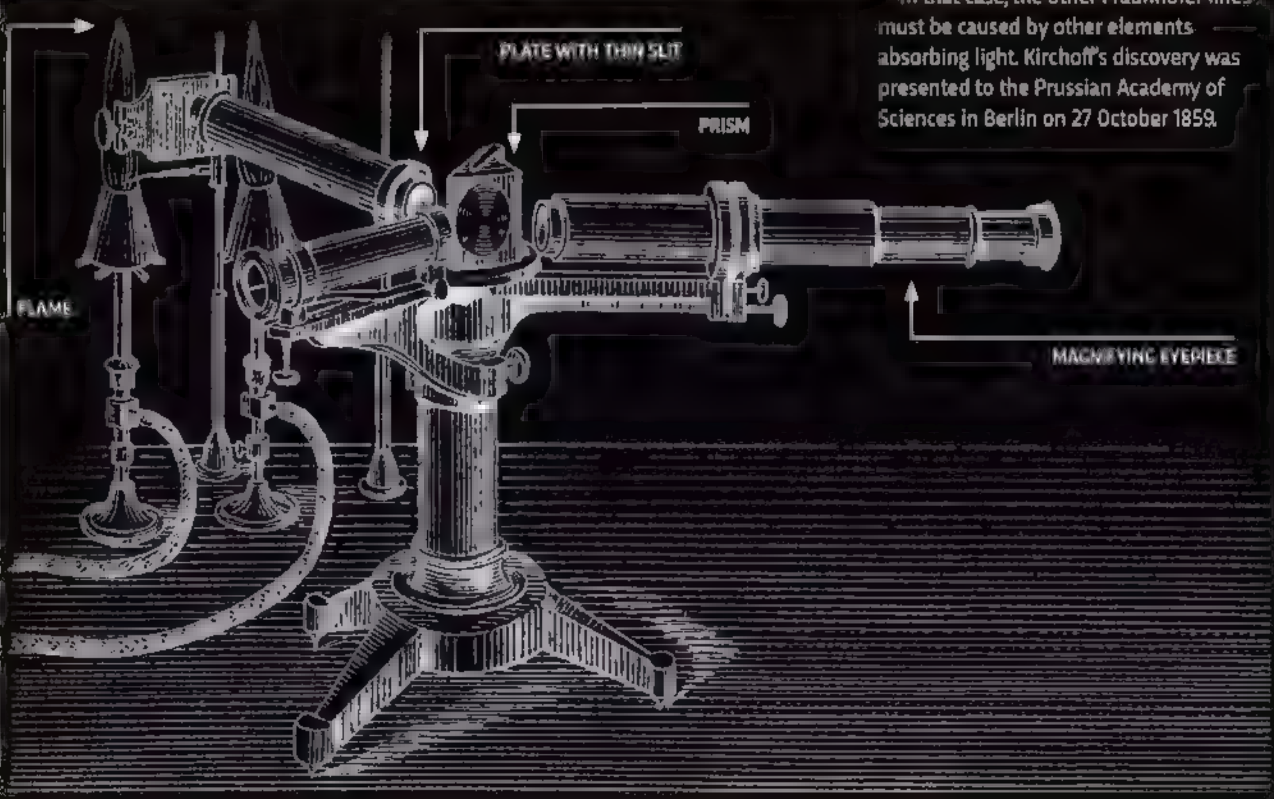
A few days later, the pair was taking a break from the lab with a walk along the Neckar River, which flows through Heidelberg, discussing what they had seen in the fire. According to legend, Bunsen remarked to Kirchhoff something along the lines of: "If we can determine the nature of substances burning in Mannheim,

THE KEY EXPERIMENT

By studying the spectrum of the Sun, Robert Bunsen and Gustav Kirchoff mastered spectroscopy and could see for the first time the elements that make up our nearest star

After their observations of the fire in the city of Mannheim, Bunsen and Kirchoff wondered if they could analyse sunlight in the same way. They looked at the lines associated with sodium in flame tests, and tried to find out if these bright lines exactly matched the corresponding dark lines in sunlight. To do this, they reflected sunlight through the flame of a Bunsen burner, that had been 'doped' with a little sodium, and analysed its spectrum. They expected that if both lines had exactly the same wavelength, the dark solar line would be 'filled in' by the bright sodium line. But to their surprise, they found that the dark line was made even darker. Kirchoff quickly realised that sodium in the flame was actually absorbing some of the sunlight, and that therefore these particular dark lines in the solar spectrum were being caused by sodium in the Sun's atmosphere absorbing light from below.

In that case, the other Fraunhofer lines must be caused by other elements absorbing light. Kirchoff's discovery was presented to the Prussian Academy of Sciences in Berlin on 27 October 1859.



The spectroscope that Bunsen and Kirchoff used to study sunlight. In doing so, they discovered some of the elements in the Sun

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we should be able to do the same thing for the Sun. But people would say we have gone mad to dream of such a thing."

Nevertheless, they turned their attention to the spectrum of the Sun and found that many of the dark lines found by Fraunhofer were in the same part of the spectrum – at precisely the same wavelengths – as the bright lines produced by various elements when heated in the lab.

The implication was that these elements are present in the outer layer of the Sun. It was thought that, as light from the hot interior passes through this region, these elements remove light from the spectrum at specific wavelengths instead of adding bright lines to it. Kirchhoff, in particular, developed this understanding of what was going on.

Nobody at that time knew precisely how the lines were produced. But even without that understanding, in the 1860s it became possible to find out what the Sun was made of – and, using the same technique, what the stars were made of.

Referring back to their riverside conversation, Kirchhoff is said to have told his colleague, "Bunsen, I have gone mad." Bunsen replied, "So have I, Kirchhoff!"

Stellar discovery

In the last decades of the 19th century, astronomers were able to identify the presence of many elements found on Earth in the spectrum of the Sun and, with less detail, the stars. The natural assumption they made was that the overall composition of the Sun was rather like the overall composition of Earth. But this turned out to be wrong. Stars are much simpler than that and we now know that they (the Sun included) are mostly composed of hydrogen and helium with just traces of the other elements.

But at the beginning of the 1860s, nobody even knew there was such a thing as helium. Its discovery marked the coming of age of solar – and stellar – spectroscopy.

The leading light in the discovery of helium was the British astronomer ❯

GETTY

WHAT WE STILL DON'T KNOW ABOUT STARS

An artist's impression of a supernova explosion

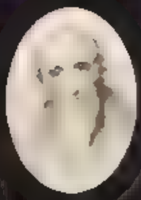
What conditions made star formation possible?

The mechanics of supernovae

Are there Population III stars?

TIMELINE

1802



William Hyde Wollaston publishes his analysis of astronomical spectra in the *Philosophical Transactions of the Royal Society*. He was the first person to notice the presence of dark bands in the Sun's spectrum.

1814

Joseph von Fraunhofer begins an investigation of the dark lines in the solar spectrum, which become known as Fraunhofer Lines. He accurately measured the wavelengths of nearly 600 of these lines.

1859

Robert Bunsen (left) and **Gustav Kirchhoff** detect spectral lines produced by strontium and barium in a fire raging at Mannheim, 16km away from their lab in Heidelberg.

1868

Pierre Janssen and **Norman Lockyer** independently discover lines in the spectrum of light from the Sun that do not correspond to those produced by any known element. Dubbed helium, the element was not found on Earth until 1895.

1925

Cecilia Payne presents her PhD thesis in which she provides measurements implying that the Sun is overwhelmingly composed of hydrogen.

1928

Albrecht Unsöld also suggests that hydrogen really is the most common stellar element. A year later, **William McCrea** (right), a research student at Cambridge University, confirms the result.

Norman Lockyer. His greatest achievement came on 20 October 1868 when he analysed light from the outer layers of the Sun with a new spectroscopic instrument. These observations followed hot on the heels of a spectroscopic study of the outer layers of the Sun during an eclipse visible from India on 18 August that year. The observations were made by the French astronomer Pierre Janssen. With the Moon blocking out the bright light from the surface of the Sun, he could detect lines in the spectrum of the material just above the surface. He noticed bright lines in the spectrum of this layer of the Sun's atmosphere, known as the chromosphere, including a bright yellow line, close to but distinct from the sodium lines. Its wavelength was later measured as 587.49 nanometres.

On 20 October that same year, unaware of Janssen's work, Lockyer used his new spectroscope to observe the solar atmosphere and found the same yellow line. Both Janssen's and Lockyer's discoveries were presented to the French Academy of Sciences on 26 October 1868. But it was Lockyer who took things a step further by claiming that the line must be associated with a previously unknown element, which he called helium, from the Greek word for the Sun: helios.

This was a controversial claim. But in 1895, the physicist William Ramsay found that a previously unknown gas released by uranium produced a bright yellow line near to the sodium lines in the spectrum. He initially called this gas krypton. But when his colleague William Crookes pointed out that the line was in exactly the same place as the one found in the solar spectrum by Lockyer, Ramsay realised it was in fact helium. In effect, spectroscopy had predicted the discovery of helium on Earth, 27 years in advance.

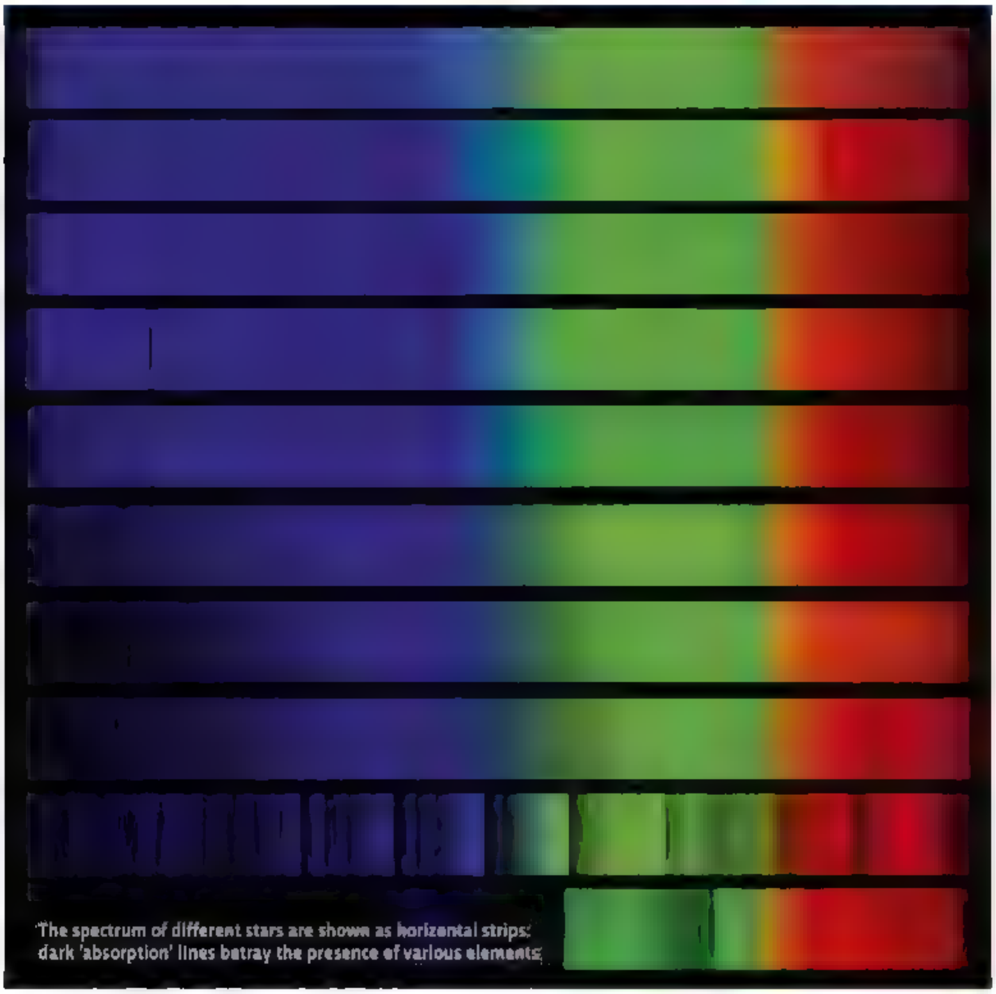
Payne the pioneer

The next step was taken by Cecilia Payne. Born in 1900, she won a scholarship to Newnham College, Cambridge in 1919, where she studied botany, physics and chemistry, but could not be awarded a degree (Cambridge did not award degrees to women until 1948). So, in 1923, she left for the United States. Just two years later, she produced a brilliant thesis and established that the Sun is made mainly of hydrogen. But, in a sign of the times, the idea was not fully accepted until two male astronomers came to the same conclusion.

By the 1920s, physicists knew (as, of course, Bunsen and Kirchhoff had not) that atoms are composed of a tiny central nucleus, with one or more electrons in orbit around it. Dark lines in a spectrum are produced when an electron absorbs a specific wavelength of light, moving to a higher energy level within the atom. Bright lines are produced when an electron drops down from one energy level to another and emits radiation (in the form, we would now say, of a photon of light). Payne measured the absorption lines in stellar spectra and showed how the temperature (in particular) and pressure in the atmosphere of a star affects the ionisation of the atoms there. Ionisation is when an atom or molecule gains or loses electric charge (see 'Need to Know', opposite). The spectra of stars differ from one another not because they are made of different things, but due to different amounts of ionisation in their atmospheres.

Payne unravelled this complicated pattern of hundreds of Fraunhofer lines and worked out what proportion of different elements in different stages of ionisation had to be present to account for the observations. She calculated the proportions of 18 elements in the Sun and stars, discovering they all had nearly the same composition. But the big surprise was that the Sun and stars are made almost entirely of hydrogen and helium. Everything else put together made up only two per cent of the composition not only of our nearest star, but of all stars. Most of the matter in the Universe was in the form of the two lightest elements – hydrogen and helium.

Such a notion was almost unbelievable in 1925, but Payne believed her results were correct. Yet when her supervisor Harlow Shapley


The spectrum of different stars are shown as horizontal strips: dark 'absorption' lines betray the presence of various elements

"Most of the matter in the Universe was in the form of the two lightest elements – hydrogen and helium"

sent a draft of her thesis to Henry Norris Russell at Princeton for a second opinion, he replied that the result was "clearly impossible".

On Shapley's advice, Payne added a sentence to her thesis saying that "the enormous abundance derived for these elements [hydrogen and helium] in the stellar atmospheres is almost certainly not real". But with the thesis accepted and her doctorate awarded, she wrote a book called *Stellar Atmospheres*.

Second opinion

The book was enough to persuade astronomers that Payne's results were almost certainly accurate. This change of mind was aided by the independent confirmation of Payne's results by her fellow astrophysicists.

In 1928, the German astronomer Albrecht Unsöld carried out a detailed spectroscopic analysis of the light from the Sun. He found that the strength of the hydrogen lines implied that there are roughly a million hydrogen atoms in the Sun for every atom of anything else. The following year, the Irish astronomer William McCrea confirmed these results using a different spectroscopic technique.

Although many details remained to be uncovered, by the end of the 1920s astronomers knew what the philosopher Auguste Comte had declared would forever remain beyond our comprehension – that the Sun and stars alike are mostly made of hydrogen and helium, with traces of other elements in proportions that can be measured using spectroscopy. SF

by DR JOHN GRIBBIN

Dr Gribbin is a science writer and Visiting Fellow in astronomy at the University of Sussex

NEED TO KNOW

[illegible]

FLAME TEST

[illegible] characteristic colour, yellow in the case of sodium.

ION

[illegible]

STELLAR SPECTROSCOPY

This is the study of the spectra of starlight. In a hot gas [illegible] the electrons absorb [illegible] stars are made of.

MEASURING THE SPEED OF LIGHT

It's the universal speed limit and the key to making sense of the cosmos. But just how were scientists able to deduce how fast light can travel? *Frank Close* investigates

Ancient Greek mathematician Euclid believed that sight occurs because the eye emits light. Hero of Alexandria pronounced that light must travel at infinite speed as distant stars appear the instant that one's eyes open. And, in the 11th century, the Basran mathematician Alhazen wrote his *Book of Optics* in which he argued that light moves from object to eye with a finite speed that varies depending on the medium through which it passes. So for example light moves more slowly through water and glass than it does through air.

Ideas continued to flow. In the 13th century, Roger Bacon used Alhazen's ideas to support the theory that light travels at a very high speed, faster than sound but finite. The idea that light travels infinitely fast in empty space, but slows down in a medium, was also believed at that time.

As late as the 17th century, luminaries, such as Johannes Kepler and René Descartes, insisted that light travels infinitely fast. Kepler argued that this must be so, as empty space would offer no resistance to its passage. Descartes based his arguments on observation: during a lunar eclipse the Sun, Earth and Moon would be noticeably out of alignment if light travelled at a finite speed – and the absence of such misalignment convinced him that light travels instantaneously.

It was around this time that the first attempts to make a direct measurement were made. In 1629, the Dutch philosopher Isaac Beeckman proposed an experiment wherein the flash of a cannon was reflected by a mirror about a mile away and the time lapse measured. Galileo independently proposed a similar experiment, involving the uncovering of a lit lantern, which was carried out by his students in 1667. No time delay was detected, confirming the prejudice that light travels infinitely fast.

With our modern knowledge of light's speed, we know it would have taken about one hundred-thousandth of a second for it to make the round trip. That's less than the reaction time of the observers, hence their inability to measure any delay – the distances involved were simply too small. By contrast, the distances between the planets are so large that light takes several minutes to travel between them. All you need is some reference against which events can be measured.

Alhazen's *Book of Optics*, a key medieval science text

International partners

In Paris, Giovanni Cassini had been observing Jupiter's moons, which disappear behind the planet as they orbit it. His measurements varied and he attributed this variation to light having a finite speed. Danish astronomer Ole Rømer joined Cassini and, in 1676, noticed that the time that Jupiter's innermost moon Io, takes to reappear is less when the Earth is approaching Jupiter than when it's receding from it.

This confirmed Cassini's conjecture that when Earth is approaching Jupiter, it has moved nearer while the light is en route and so the total

IN A NUTSHELL

How fast light can travel is a question that scientific minds have been grappling with since ancient Greece. Today we can measure the speed of light very precisely, but it took hundreds of years and many theories to get to where we are now.

The Draco constellation. From noting the movement of one of its stars, 18th-century astronomer James Bradley deduced a speed for light

"The apparent position of a star varies during the year, due to a phenomenon known as aberration"

distance for the light to travel is less. Hence it arrives relatively early. Conversely, when we are travelling away, the light has to travel further and arrives relatively late. Rømer's measurements – along with his discovery of the correlation with Earth's motion – caused him to be credited with the discovery. In 1690, Dutch mathematician Christiaan Huygens used this to estimate a speed for light of around 220,000km/s, about 70 per cent of the modern value.

The next step in the story again involves astronomy, in this instance the aberration of light, which may be illustrated by a familiar phenomenon: keeping dry as you move through falling rain. Rain that is falling vertically when you're at rest appears to be falling from a point in front of you as you walk forwards – you have to tip your umbrella to keep dry. Walk in the opposite direction and the origin of the raindrops now also appears to be in the opposite direction. Now think of the falling rain as light travelling from a distant star and your motion being that of Earth through the heavens. The apparent position of a star varies during the year due to this phenomenon, known as aberration.

James Bradley, the Astronomer Royal, discovered this phenomenon in 1729. He made measurements of a star in the constellation Draco and found that its position moved first south and then north on a six-month cycle. The motion was little more than 1/100th of a degree, but this could be seen easily enough with 18th-century equipment. From this, Bradley deduced that light travels about 10,200 times faster than Earth in its orbit, 295,000km/s, an estimate that is within about two per cent of the modern value.

Back down to Earth

To determine high speed requires either access to large a distance, as in astronomy, or the ability to measure very small time intervals. The French physicist Hippolyte Louis Fizeau in 1849 found a way to do this on Earth.

Fizeau shone light between the teeth of a rapidly rotating wheel. A mirror five miles away reflected the light back. If the light passed through a gap, it would be seen, but if it hit a tooth between gaps, darkness would ensue. He varied the speed of rotation and from this was able to determine how long the light had taken to make the round trip. Knowing the distance to the remote mirror, he was able to infer the speed, some 313,000km/s. In 1862, Léon Foucault used a similar idea, but with rotating mirrors to determine the angle through which the light had been deflected. He found a speed of 299,796km/s, remarkably close to the modern value of 299,792.46km/s.

In 1865, the Scottish physicist James Clerk Maxwell published his work on electromagnetic waves, in which light is a wave of electric and magnetic fields. In any electromagnetic wave, an electric field disappears and a

ALAMY

> "In 1690, Dutch mathematician Christiaan Huygens used this to estimate a speed for light of around 220,000km/s, about 70 per cent of the modern value"

THE KEY EXPERIMENT

How observing the movement of Jupiter's moons provided 17th-century astronomers Giovanni Cassini and Ole Rømer with an early indication of the speed of light

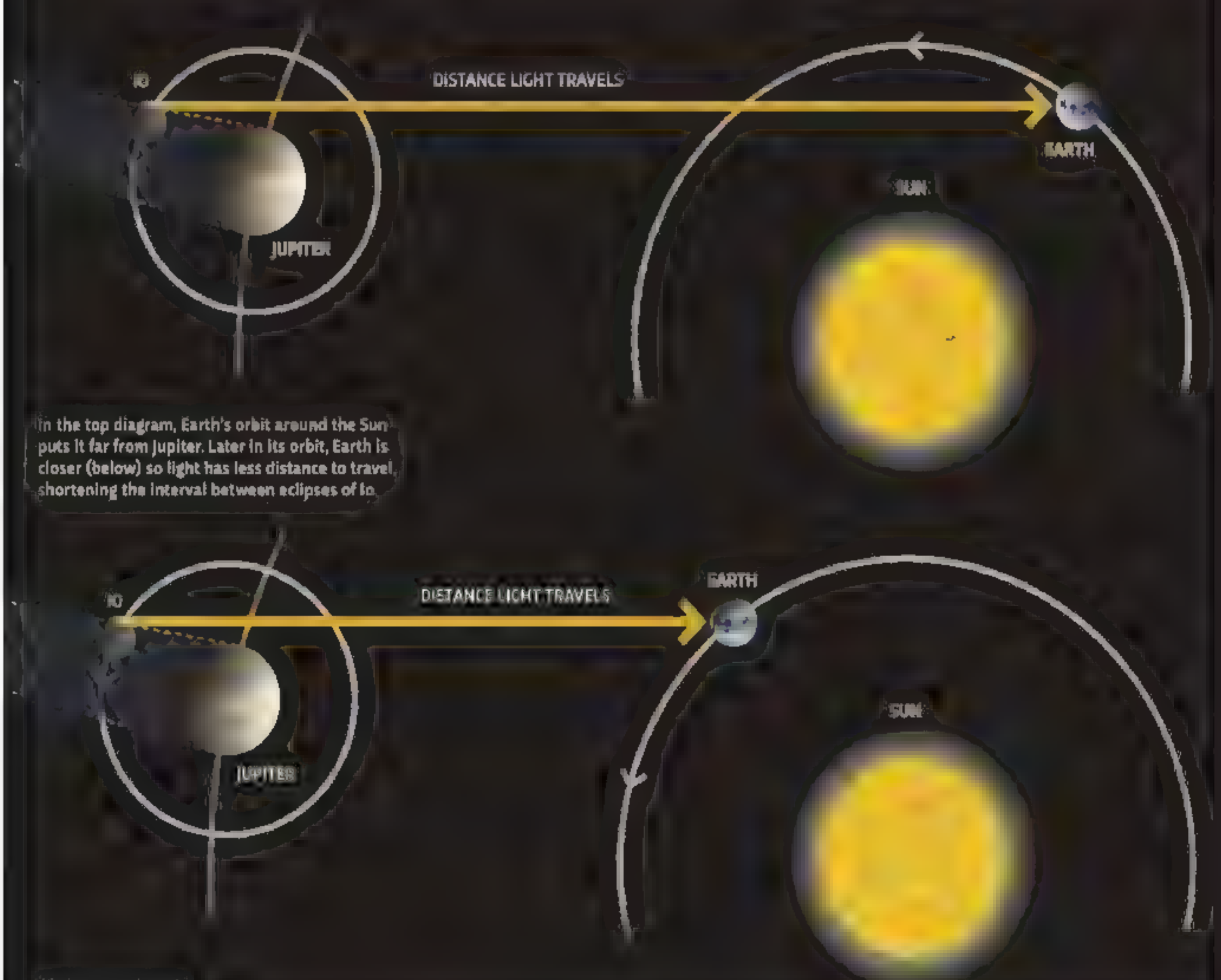
Io, the innermost moon of Jupiter, orbits that planet every 42.5 hours. Viewed from Earth, Io periodically disappears behind Jupiter and reappears later. It was thought that the time between eclipses would be the same.

However, when Giovanni Cassini made measurements around the year 1671, the results kept changing. He realised that this could be due to light taking time to travel from Jupiter to Earth, during which period the Earth had moved. Therefore, the distance travelled from Jupiter to Cassini's telescope would vary from one eclipse to another, depending on whether Earth was moving towards or away from Jupiter.

Cassini seems not to have trusted his intuition, but his assistant, Ole Rømer, performed his own measurements. When these were combined with Cassini's, Rømer realised that the variations correlated with the relative motion of Earth and Jupiter.

Rømer made a long series of measurements that established this, as well as leading to an estimate of light's speed to be in excess of 220,000km/s. For many, this was so unimaginably fast as to be regarded as infinite and Rømer's ideas were not universally believed.

It was not until 1729 when Astronomer Royal James Bradley measured the speed of light by means of stellar aberration that Rømer's theory was finally accepted.

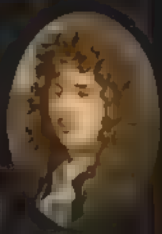


In the top diagram, Earth's orbit around the Sun puts it far from Jupiter. Later in its orbit, Earth is closer (below) so light has less distance to travel, shortening the interval between eclipses of Io.

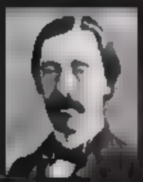
Diagram not to scale

TIMELINE

1690



After Ole Rømer shows that light travels at a finite speed, fellow Dane Christiaan Huygens calculates this speed to be around 220,000km/s.



1862

French physicist Léon Foucault uses rotating mirrors to calculate the speed of light at 299,796km/s.

1865

James Maxwell shows light to be an electromagnetic wave, enabling its speed to be calculated from known properties of space.

1905

The concept that the speed of light is universal, independent of the speed of the source or of the observer, forms the basis of the Special Theory of Relativity developed by Albert Einstein (above).

1972

A laser (below) is used to measure the frequency of a particular spectral line of a krypton atom. By combining this information with the definition of the metre, the speed of light in a vacuum is measured as 299,792,458m/s.

1983

Light speed is made absolute at the 17th General Conference on Weights and Measures. As a result, a metre is now defined as 1/299,792,458th the distance travelled by light in a vacuum in one second.

> "Precise measurements of the speed of light had led to profound new insights into the nature of space and time, courtesy of Einstein"

magnetic field emerges, and vice versa, over and over. The resistance or 'stiffness' of free space to the former is called its electric permittivity, while its resistance to the magnetic field is called its magnetic permeability. In Maxwell's theory, the speed of light is related to these quantities. The ease with which the electric and magnetic fields can oscillate back and forth determines the speed at which the electromagnetic wave travels. It turns out that the product of these quantities is proportional to the inverse of the square of the speed of light.

So, in a sense, Kepler was right, centuries ago. If space offered no resistance – in Maxwell's theory, if the electric or magnetic 'stiffness' were zero – the speed of light would indeed be infinite. But in reality, the electric and magnetic 'stiffness' are not zero and, when their values were inserted into Maxwell's equations at the end of the 19th century, they gave a value of 299,788km/s, then the most accurate estimate of the speed of light available.

In the USA in 1887, Albert Michelson and Edward Morley attempted to measure the speed of Earth through the 'ether' (a medium then believed to permeate all space) by measuring the difference in the speed of light in two perpendicular directions. They used semi-transparent mirrors, which deflected light through 90° while also allowing some to carry on unhindered. By reflecting the two beams back along their paths and recombining them, any difference in speed would show up by the two waves being out of phase – a mismatch between their peaks and troughs that would show up as a subtle set of dark and light fringes, known as an interference pattern.

Onwards to Einstein

Michelson and Morley's set-up proved highly sensitive and, to their surprise, demonstrated that the speed of light is universal, independent of direction. In turn, this led Albert Einstein to insist that the ether does not exist (at least in the form then believed) and to propose his theory of Special Relativity in 1905. Thus precise measurements of the speed of light had led to profound new insights into the nature of space and time, courtesy of Einstein.

In particular, Einstein's theory implies that the speed of light in a vacuum is nature's speed limit: no object that has mass can ever attain the speed of light in a vacuum, while any particles that have no mass must travel through a vacuum at this universal speed. But light is slowed when it passes through a transparent medium, such as water or glass; it is possible for particles, such as an electron, to travel through the medium faster than light, but still below the absolute speed limit.

Before the invention of the laser, independent measurements of the frequency and wavelengths of electromagnetic waves were made in the 1950s using 'cavity resonators', which gave a value of 299,792km/s with an uncertainty of 3km/s. A modern demonstration is to put a chocolate bar in a microwave oven. Remove the turntable so the specimen is stationary and it will cook fastest at the points where the waves are most intense. The distance between two successive spots is half the wavelength of the microwaves. Multiply the wavelength by the microwave frequency (typically 2,450MHz, but check with your manual) and the speed of light results, though with less accuracy than in the 1950s laboratory.

Modern large-length experiments involve sending radio signals to different spacecraft whose positions in the Solar System have been precisely calculated, allowing for the gravity of the Sun and planets.

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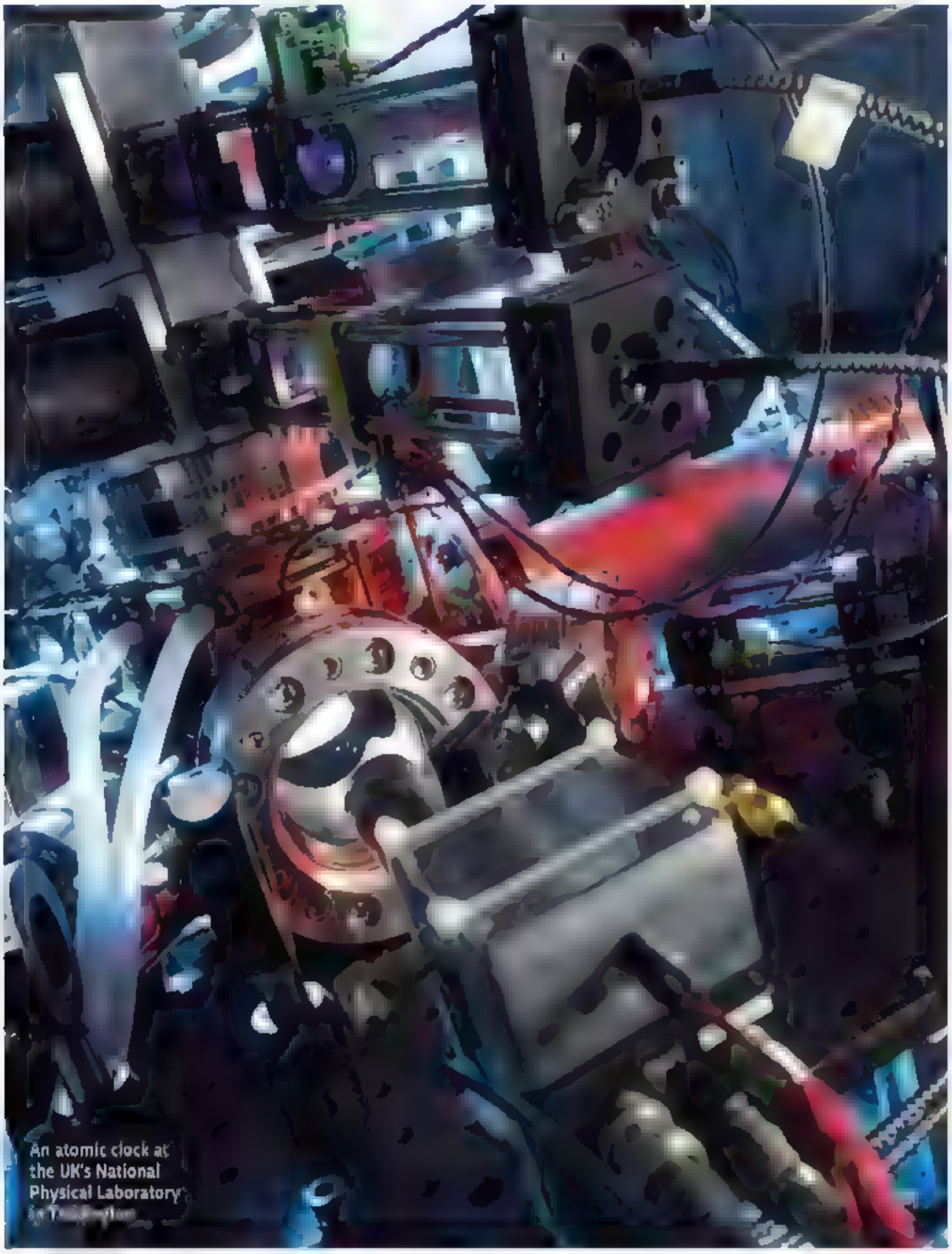


An atomic clock at the UK's National Physical Laboratory [illegible]

This enables the speed of light to be calculated to an accuracy of 20 parts per trillion.

Modern descendents of the Michelson-Morley technique use a laser beam whose frequency is known precisely. After the beam is split into two paths and then recombined, the interference pattern can be decoded to determine the wavelength of the light. The speed is then the product of this wavelength and the frequency. In 1972, this led to a precision in the measurement of the speed of better than four parts per billion.

Today, advanced lasers and the measurement of time intervals using atomic clocks provide the most accurate value of 299,792,458m/s, with an uncertainty of just one metre per second. The second can be defined precisely using atomic clocks and the remaining uncertainty in the speed of light is due the accuracy of defining a metre. As such, since 1983 it has been agreed to 'fix' the speed of light at the above value and to define the metre so that there are exactly 299,792,458 of them in the distance that light travels in a vacuum in one second. So today, instead of measuring the speed of light relative to the space-time of the Universe, as physicists struggled to do for centuries, we use the speed of light determine the latter. **SF**

by FRANK CLOSE

Frank is Emeritus Professor of physics at the University of Oxford

NEED TO KNOW

ABERRATION OF LIGHT

[illegible]

ATOMIC CLOCK

[illegible] have. It u[illegible] the frequency of microwave [illegible]gnals that electrons in atom[illegible] they change [illegible]nergy leve[illegible]

CAVITY RESONATOR

[illegible] both ends, along whic[illegible]

ELECTRIC PERMITTIVITY

[illegible] permittivity, it can [illegible] determined using capacitors [illegible]

MAGNETIC PERMEABILITY

[illegible]

THE NATURE OF GRAVITY

What goes up must come down... But why that's the case is a mystery that took some of humanity's greatest minds centuries to figure out. And, as *Brian Clegg* explains, some aspects of gravity continue to remain a puzzle

There are four fundamental forces that operate in the Universe: the strong nuclear force, the weak nuclear force, the electromagnetic force and gravity. Gravity is the most obvious of these yet it has proved a very difficult puzzle to crack.

To the ancient Greeks, gravity reflected the nature of the elements. Aristotle described how earth and water had gravity, and there was a tendency of motion towards the centre of the Universe (Earth).

The great 7th-century Indian mathematician Brahmagupta briefly flirted with the idea that gravity might work in a similar way to a magnet, as did the Islamic scholar al-Biruni 300 years later. But this wasn't enough to shake Aristotle's theoretical dominance, which survived for around 2,000 years.

> "Newton realised gravity was responsible for keeping the planets in their orbits, stopping them from flying off in a straight line"

The first cracks appeared with the transformation of the Solar System by Copernicus and Galileo. If they were correct – that Earth travelled around the Sun – then Aristotle's model of gravity fell apart. Based on reasoning rather than observation and experiment, Aristotle's ideas required Earth to be the centre of the Universe. If it were the Sun instead, all heavy matter should fly off into space.

What's more, Aristotle's model of gravity made heavy objects fall faster than light ones. With more material in them, the heavy objects should feel a stronger urge and therefore move faster. Aristotle stated this as fact, yet Galileo demolished the idea. He asked what would happen if you tied together two objects of different weight. The heavier weight, according to Aristotle, would want to fall faster and would speed up the lighter one – but the light weight should slow down the heavier one, leaving them falling at an intermediate speed. Yet the combined object was heavier than either, so the whole should fall faster. It didn't make sense.

Although Galileo almost certainly didn't drop weights off the Leaning Tower of Pisa to discover that they arrived at the ground at the same time, as popular legend has it, he did experiment with pendulums that had bobs made of cork and lead, one "more than 100 times heavier" than the other, and showed that they swung (and hence fell under gravity) at the same rate. He also repeatedly rolled balls down sloping channels to measure the effects of gravity.

But it was Isaac Newton who brought gravity fully under the auspices of science and mathematics. It's not clear whether he was truly inspired to do this by seeing an apple fall from a tree, even though he did make this claim (it certainly didn't fall on to his head). In a long chat with the antiquarian William Stukeley in April 1726, the elderly Newton described how the fall of an apple made him think, "Why should the apple always descend perpendicularly to the ground?"

In Stukeley's account, Newton says that the apple is pulled by a 'drawing power' to Earth and that this force must be proportional to its quantity. The apple draws Earth and Earth draws the apple. But more than this, Newton made the leap of proposing 'universal gravitation'. He broke Aristotle's lunar barrier and applied the same force throughout the Universe, realising that gravity was responsible for keeping the planets

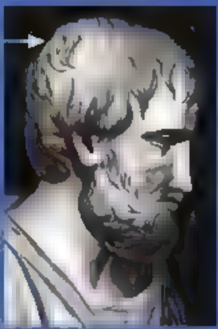
GETTY

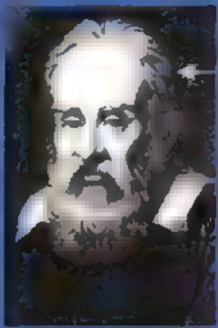
IN A NUTSHELL

The ancient Greeks thought that earth and water were drawn towards the centre of the Universe, then believed to be Earth. But thanks to Galileo, Newton and Einstein, our knowledge of this fundamental force has come a long way since the 4th century BC

CAST OF CHARACTERS

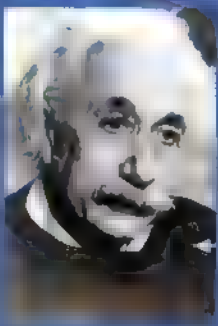
ARISTOTLE (384-322 BC)
The definitive ancient Greek philosopher Aristotle set the agenda for science for more than 1,800 years. This is a pity, as his theories – based on reasoning rather than observation – were almost universally misleading. Gravity, as Aristotle saw it, was a tendency for heavy things to prefer the centre of the Universe.





GALILEO GALILEI (1564-1642)
This natural philosopher believed in the importance of experiment and, as a result, dismissed Aristotle's ideas on gravity. Though famous for being tried for promoting the Copernican model of the Solar System, Galileo's greatest contribution was his methodical exploration [illegible]anics and motion, including the influence of gravity.

ISAAC NEWTON (1643-1727)
The greatest English physicist. Most of his work on light, motion, gravity and calculus was done in Cambridge, though much was achieved when he was confined to his home in Lincolnshire due to the plague. He was later an MP, Master of the Mint and President of the Royal Society but physics remains his most significant [illegible]



ALBERT EINSTEIN (1879-1955)
Einstein was born in Ulm in Germany though he was a Swiss citizen from his teens. He produced three papers in 1905, while working in the patent office, that would show atoms were real, lay the foundations of quantum theory and establish Special Relativity. His theory of General Relativity from 1915 is still the standard theory of gravitation.

ARTHUR EDDINGTON (1882-1944)
Born in the Lake District, Eddington worked as an astronomer and astrophysicist in Cambridge. When asked if it were true that only three people in the world understood the theory of General Relativity, Eddington is said to have replied, "Who is the third?"

➲ in their orbits and stopping them from flying off in a straight line. All this and more Newton included in his masterpiece, *Philosophiae Naturalis Principia Mathematica*, usually known as the *Principia*. The book, originally written in Latin, is not easy to read and relies far more on geometry than we would expect today, but here we get the understanding that the force of gravity is dependent on the masses of the objects involved divided by the square of the distance between them. This and his laws of motion were enough for Newton to describe the way that planets and moons move and the way that things fall when they drop. It was, without doubt, a triumph.

But Newton did leave one aspect hanging: how this strange force acting at a distance could work.

Gravity explained

In 1905, Albert Einstein wrote three papers that transformed physics. These established the existence of atoms, formed the foundations of quantum theory and introduced Special Relativity, which showed how apparently fixed quantities such as mass, length and the flow of time varied depending on your viewpoint.

Two years later, Einstein was sitting in the patent office in Bern and had what he described as his happiest thought. "All of a sudden a thought occurred to me: if a person falls freely, he will not feel his own weight. I was startled. The simple thought made a deep impression on me. It impelled me towards a theory of gravitation."

What Einstein had realised was that gravity and acceleration were equivalent and indistinguishable. If, for instance, you were in a spaceship with no windows and found that you were experiencing a pull of 1G, there are two possible explanations. You could be sitting still on the surface of Earth or you could be in space and the craft could be accelerating at 9.81m/s per second – the same acceleration as due to Earth's gravity. Your instruments could not detect a difference. But if this is true, it tells us something odd about gravity.

If we imagine a beam of light

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String theory, also known as M-theory is an atte[...] reconcile gravity [...] quantum mechanics

crossing the accelerating spaceship, the beam will appear to bend to someone inside the ship as a result of its motion. But since acceleration and gravity are equivalent, the same light beam should also bend in a gravitational field. Einstein had realised that gravity warps space, twisting it near a massive body so that anything travelling in a straight line curves around it. This is also true of an orbiting planet.

In fact, his discovery proved stranger still. While the warping of space explains the orbits of the planets, it doesn't tell us why the apple falls. There is no reason for something to start moving. But it is space-time – the mash-up of space and time that emerged from Special Relativity – that is warped by massive objects, and it is the warp that initiates motion. The mathematics to support all this is fiendishly complex, but the principle is simple enough.

Einstein had given Newton's theory a framework, a reason for working. More than that, General Relativity, as Einstein's theory became known, made some predictions that were different from those Newton would have expected – and experiments have verified that it is General Relativity that matches reality.

It seemed in many ways that the theory of gravitation was complete. Einstein's development would be used to predict everything from the existence of black holes to the way the Universe changes with time. But there is still a big gap in our understanding. All the other forces of nature are quantised. They aren't continuous, but are granular with tiny divisions called quanta. The expectation is that there should also be a quantum theory of gravity, but as yet one has not been established. For a while, it seemed as if string theory would provide the answer, but there is increasing concern that this mathematically driven concept will never make useful predictions, leaving growing interest in alternative theories such as loop quantum gravity.

Gravity and us

Our modern understanding of gravity reveals that it's far more important than the ancients thought. Gravity not only keeps things in place on Earth, it was also responsible for the formation of the Solar System as it coalesced out of a spinning cloud of dust and gas.

Experiments in space have even shown that gravity is essential for living things – plants struggle to grow with no gravity to direct their roots, birds' eggs need gravity to develop, and human beings deteriorate in low gravity, losing bone density and muscle tone.

Gravity continues to keep hold of some secrets. We don't know, for instance, why it is so much weaker than the other forces. Nor do we know how to bring gravity into the quantum fold. But thanks to the work of those pioneers Newton and Einstein, this fundamental force is no longer a total mystery. **SF**

by BRIAN CLEGG

Brian is a science writer and author. His latest book is Professor Maxwell's Duplicitous Demon

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NEED TO KNOW

Key terms used when discussing the nature of gravity

FUNDAMENTAL FORCES

[illegible]

INVERSE SQUARE LAW

[illegible]

MASS

[illegible]

RELATIVITY

[illegible]

THE STRUCTURE OF THE ATOM

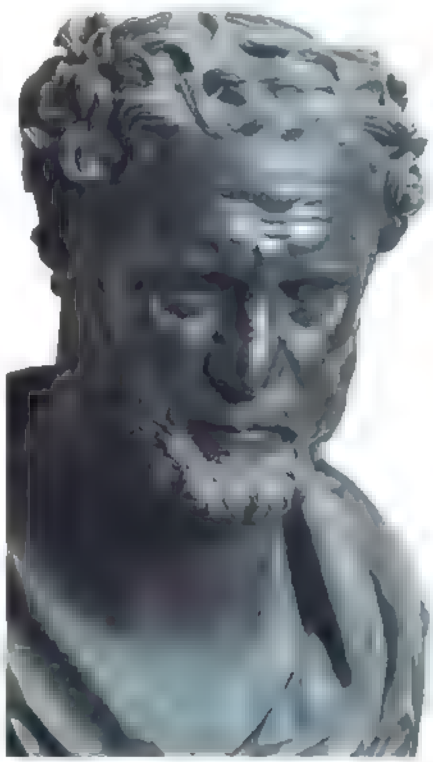
Throughout history, we've endeavoured to find out what things are made of at the smallest scales of matter. As *Frank Close* reveals, thanks to some great scientific breakthroughs, we now know the answer

Somewhere around the year 400 BC, in Ancient Greece, the philosopher Democritus asserted that all material things are made from atoms – tiny basic objects that cannot be divided into smaller pieces. "Nothing exists except atoms and empty space," ran the mantra – at least until Aristotle rejected atomic theory and the idea was ignored for nearly two millennia.

The Ancient Greeks also believed that everything was made from a few basic elements. The idea was right; the details were wrong. They thought that earth, wind and fire, along with water, were the seeds of everything. Today we know that everything is made from chemical elements, such as hydrogen, carbon and oxygen. And these elements consist of atoms, which are too small to see with the eye alone (hundreds of thousands could fit into the diameter of a human hair), but visible to special instruments.

While Democritus was right that an atom is the smallest piece of an element that is still identifiable as such, today we know of deeper layers to the cosmic onion. An atom is not the smallest thing: atoms are themselves divisible.

Today, we know that if you cut into an atom of any element, you will find its common constituents: lightweight, negatively charged electrons in the outer regions and a positively charged nucleus, dense and massive, at the centre. The only difference between the atom of one chemical element and another is the amount of electric charge on its nucleus and the number of electrons that can be ensnared by the rule 'opposite charges attract'.



The ancient Greek philosopher Democritus came up with an atomic theory of the Universe

An atom of hydrogen, the lightest element, has a nucleus with one unit of charge, encircled by one electron. Helium, the next lightest, has two and the heaviest naturally occurring element, uranium, has 92. Obtaining this knowledge took scientists on a remarkable journey of discovery.

Atomic alchemy

In the late 17th century, Irishman Robert Boyle founded the atomic theory of matter. Boyle was an alchemist, trying to find a way to change common elements, such as iron, into gold. Although he failed in this endeavour, he was the first to recognise that substances are compounds of basic elements and to propose that these elements are composed of basic particles: atoms.

Boyle's ideas were descriptive only. Quantitative chemistry only came about in the late 18th century when, in France, Antoine Lavoisier showed that the masses of individual elements stay the same – are 'conserved' – during chemical reactions. This led to the idea that basic elements were rearranging themselves in such processes. He also demonstrated that water is made from two elements: hydrogen and oxygen.

AKG IMAGES SCIENCE PHOTO LIBRARY

IN A NUTSHELL

Scientists have always probed matter to uncover its constituent parts and improvements in our understanding of physics have allowed us to find ever smaller components. By working out what's in an atom, we've built the Periodic Table of Elements and know which elements are missing.

In Britain in the early 19th century, John Dalton suggested that all atoms in a given chemical element are exactly alike; the atoms of different elements being distinguished by their mass. He had discovered that the weights of the various elements involved in chemical reactions were always in simple numerical proportions. The simplest example involved the gases, hydrogen and oxygen, combining to make water.

Measurements showed that, if all of the gases were to be used, the weight of the oxygen would need to be eight times as much as that of hydrogen. As two hydrogen atoms and one oxygen atom have combined to make a molecule of water (H_2O) it implies that one oxygen atom must weigh eight times as much as two atoms of hydrogen. So an atom of oxygen is 16 times heavier than one of hydrogen

By studying many chemical reactions and measuring the relative amounts of the elements involved, by the mid-19th century the relative masses of their basic atoms had been determined. Relative to hydrogen, atoms of oxygen, carbon, calcium and iron weighed 16, 12, 40 and 56 times as much. This tantalising numerology was a hint that atoms of different elements may share some common

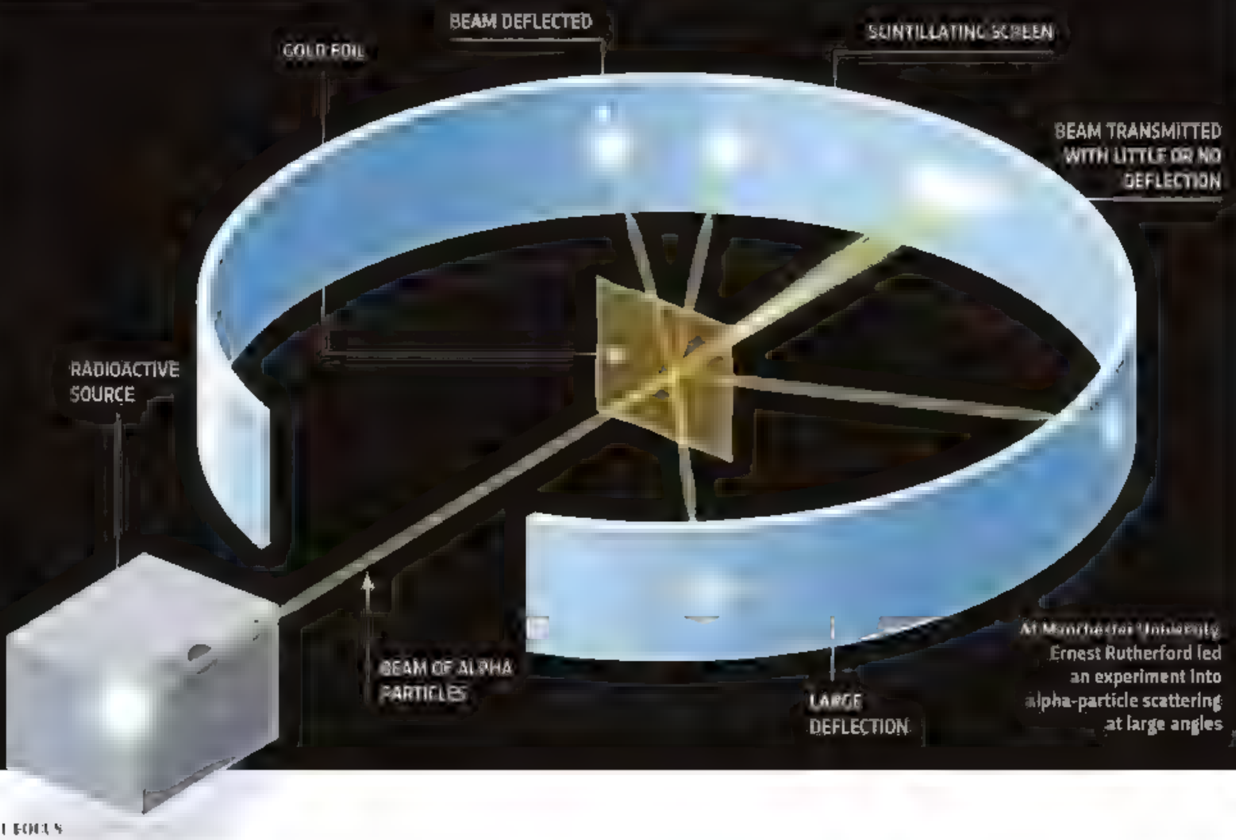
THE KEY EXPERIMENT

In his Manchester laboratory, the physicist Ernest Rutherford and his colleagues found a way to probe the heart of an atom

Early in the 20th century, Ernest Rutherford noticed that thin sheets of mica could deflect alpha particles (see 'Need to know', p37), which were moving at 15,000km/s. This could only have happened if they felt electric and magnetic forces far greater than anything known. He mused that these forces might be present within atoms. Rutherford suggested that his colleague, Ernest Marsden, look to see if any alpha particles were deflected through very large angles. Instead of mica, Marsden used gold leaf that was only a few hundred atoms thick, and a scintillating screen to detect the scattered alpha particles. To everyone's amazement, he discovered that about one in 20,000 alphas were turned back in their tracks. Rutherford famously exclaimed: "It was as though you had fired a 15-inch shell at a piece of tissue paper and it had bounced back and hit you."

Rutherford realised that the positive charge in an atom is concentrated in a massive and exceedingly compact central 'nucleus', and that it was the repulsion of like charges that was deflecting the relatively lightweight alpha (the nucleus of a gold atom being some 50 times more massive than an alpha particle).

The size of the nucleus relative to an atom was famously compared to being like a "fly in a cathedral".



At Manchester University, Ernest Rutherford led an experiment into alpha-particle scattering at large angles

ingredients, the atoms of the heavier elements having 'more' of the mystery material than the lighter ones. In other words: atoms are made of something even smaller.

Mystery components

With hindsight, by the middle of the 19th century two discoveries held the clue that atoms have an inner structure. First was the phenomenon of atomic spectra. Here, when light emitted by hot elements was split into component colours, characteristic sets of lines showed up, in effect an atomic barcode unique to each element. While chemists used the phenomenon to identify known elements and discover new ones, such as helium in the Sun, physicists found it too complicated to explain and initially ignored it.

Second, the Russian Dmitri Mendeleev discovered that, when he listed the atomic elements in order of their atomic weights, from the lightest, hydrogen, up to uranium, elements having similar chemical properties periodically reoccurred. His celebrated Periodic Table of Elements contained gaps, which led him to predict that further elements must exist to fill them. The discoveries of gallium, germanium and scandium, found in France, Germany and Scandinavia followed – you can easily tell which was found where!

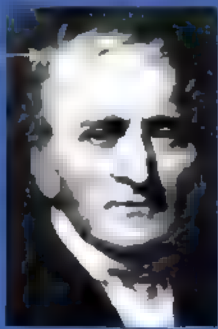
Dalton had believed that atoms were indivisible spheres. But by the end of the 19th century, clues were accumulating suggesting that atoms have an internal structure. In addition to spectra and the periodic table, radioactivity showed that one element could transform spontaneously into another by emitting particles, a process known as transmutation. This raised two questions: what were the constituent parts of atoms and how were they arranged?

Answers came in 1897, when Joseph John Thomson found that electric current is carried by negatively charged particles: electrons. Measuring the ratio of an electron's charge to its mass, he found this was very large and common to all elements that he used. From this he deduced ➲

CAST OF CHARACTERS

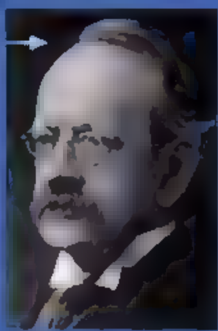
The pioneers who have peeled back the l... of the 'atom...

JOHN DALTON (1766-1844) An English chemist and founder of modern atomic theory. Born in Cumberland, he moved to Manchester where he taught mathematics and natural philosophy. He studied the behaviour of gases and the atmosphere, but his most famous insights were with the atomic theory of chemistry, with which his name is associated.



DMITRI MENDELEEV (1834-1907) A Russian chemist most famous for his Periodic Table of Elements, which he discovered wh... writing a textbook on chemistry in 1869. He was twice nominated for the Nobel Prize in 1906 and 1907, but this was rejected after claims that his discovery was too old.

JOSEPH JOHN THOMSON (1856-1940) Better known as J Thomson, he was born in Manchester and joined Trinity College, Cambridge, in 1876. He spent the rest of his life there and his work on the properties of gases and atomic structure led to his discovery of the electron, in 1897 and a Nobel Prize in 1906.



ERNEST RUTHERFORD (1871-1937) The New Zealand-born British physicist is famous for discovering the atomic nucleus, identifying forms of radioactivity and fathering the field of nuclear physics. Although he is best known for his discovery of the nuclear atom, his 1908 Nobel Prize was for chemistry and his discovery of transmutation of the elements.

NIELS BOHR (1885-1962) A Danish physicist who made major contributions to the foundations of quantum mechanics and to the theory of atomic structure. His planetary model was the forerunner of the modern picture of the atom. He won the Nobel Prize for physics in 1922.

SCIENCE & SOCIETY X2, ALAMY X2, GETTY

TIMELINE

1803

John Dalton proposes that all matter is made of indestructible atoms; that atoms of different elements are distinguished by their weights and that chemical reactions occur when atoms are rearranged.

1897

Joseph John 'JJ' Thomson (above) discovers the electron – a constituent of all atomic elements. Negatively charged, it suggests there must also exist positively charged constituents to neutralise the atom.

1911

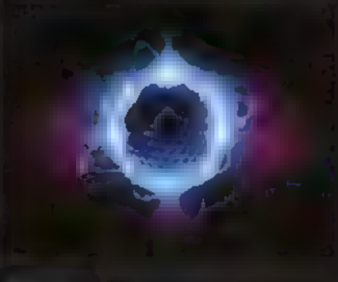
Ernest Rutherford discovers the positively charged atomic nucleus following experiments by Hans Geiger and Ernest Marsden. He realises the nucleus is massive and compact, and that an atom is mostly empty space.

1913

Niels Bohr (left) creates a conceptual picture of the atom like a miniature Solar System, where 'planetary' electrons orbit a central nuclear 'Sun'.

1925-28

Erwin Schrödinger produces a quantum theory of electron behaviour in the hydrogen atom in 1925. Three years later, Paul Dirac completes the theory, making it consistent with the theory of Special Relativity.



1932

Atomic nucleus established to consist of protons and neutrons. The proton and neutron are today known to be made of more fundamental seeds: quarks. The electron still appears to be indivisible.

that electrons are a component part that features in all elements.

American Robert Millikan measured the electric charge of the electron, which, combined with Thomson's result for the ratio of charge to mass, showed this ratio is large because the mass of an electron is tiny, only about 1/2,000th that of a hydrogen atom, the lightest atom known. This led to two inferences: one, as electrons are so light, there must be other more massive particles in there too. And, two, as atoms have no overall electric charge, the massive particles must therefore be positively charged in order to neutralise the electrons' negativity.

When Ernest Rutherford and his assistants Hans Geiger and Ernest Marsden bombarded atoms of gold with alpha particles – massive, positively charged particles emitted in radioactivity – they found that most of them passed through, but occasionally one would recoil violently (see 'The Key Experiment', page 34). In 1911, Rutherford deduced that the gold atom must be mostly empty space, but with a dense massive central region, capable of deflecting the alpha particles. He called this the nucleus.

The nucleus of a hydrogen atom is the simplest of all, consisting of a single positively charged 'proton'. The nuclei of heavier elements contain several protons – helium has two, uranium has 92 – whose combined positive charge ensnares negatively charged electrons to form the atom. It is the larger number of protons in atoms of elements, such as uranium, that helps give them a larger atomic weight than hydrogen.

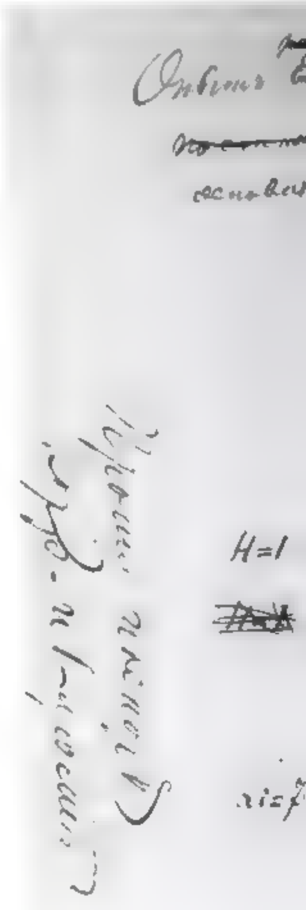
Weighty issue

But protons alone don't explain the exact values of the atomic weights: in addition to protons, all elements other than hydrogen contain neutrons, which have no electric charge. Neutrons add to the mass of the atom but leave its chemical properties unchanged. A given elemental atom can occur with different numbers of neutrons. Such alternatives are known as isotopes. Even hydrogen has isotopes: 'heavy water' is the result of a hydrogen atom having a proton and a neutron.

When Rutherford's discovery of the positively charged atomic nucleus and Thomson's discovery of the lightweight, negatively charged electron were married with the rule that opposite electrical charges attract, a seductively simple picture emerged of the atom as a miniature Solar System. In this naive analogy, the nucleus plays the role of the Sun and electrons are like the remote planets in orbit around it.

However, had electrons in atoms encircled the central nucleus like planets orbiting the Sun, obeying Newton's laws of motion, they would have spiralled into the nucleus within a mere fraction of a second. An atom, once formed, would self-destruct in a flash of light almost immediately; matter would not exist. Something was missing. The final ingredient was the discovery of quantum theory: very small things, such as atoms, follow different laws from those of Newton, which explain the behaviour of objects that are large enough to see. Instead of an electron being able to go anywhere in an atom, it is limited, like someone on a ladder who can only stand on one rung at a time. Electrons in atoms follow a fundamental regularity, each rung corresponding to a state where the electron has a unique amount of energy.

Danish physicist Niels Bohr suggested the idea in 1912. When an electron drops from a rung with high



Mendeleev's 1869 periodic table had gaps that led him to believe that some elements remained undiscovered

SCIENCE & SOCIETY X2, NASA

> "An elemental atom can occur with different numbers of neutrons. Such alternatives are known as isotopes"

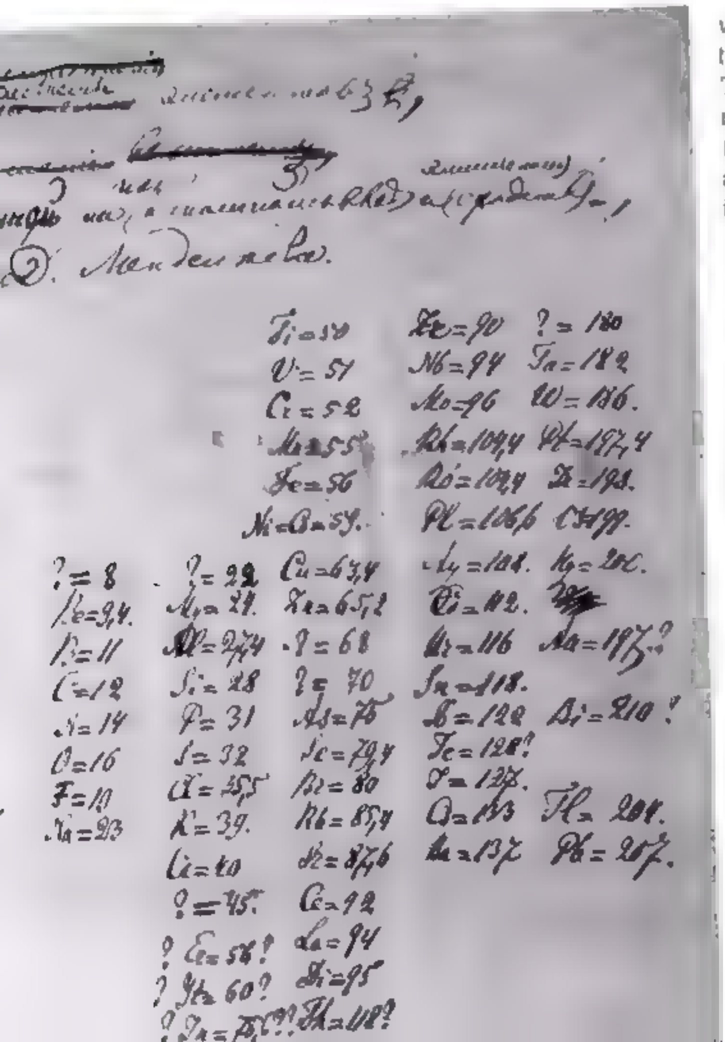
energy to one that is lower down, the excess energy is carried away by a photon of light. Conversely, if an atom is hit by a photon whose energy matches the gap between two rungs, the atom absorbs that photon, lifting the electron up the ladder.

Light fantastic

This absorption effect became obvious when sunlight was examined. Like all stars, the Sun emits electromagnetic radiation across the entire spectrum. It also has a lot of gas in its outer atmosphere, containing a smorgasbord of elements. In sunlight, the photons with energies that happen to match the gaps between rungs in the atomic ladders are absorbed by the atoms of these elements and never reach Earth. By viewing starlight through a diffraction grating (a piece of glass scratched with close-packed grooves), you split light into its component colours. These 'missing' photons show up as dark lines.

Quantum theory goes further in explaining where electrons can be around a nucleus. Any particle can take on a wave-like character. What is familiar for electromagnetic waves occurs for electrons too. Imagine the waves for electrons in atoms as if they were wobbles on a length of rope. When coiled like a lasso, the number of wavelengths in the circuit has to fit perfectly into its circumference. Imagine this circle like a clock face. If the wave peaks at 12 o'clock, with a dip at 6 o'clock, the next peak will occur perfectly at 12: the wave 'fits' into the circle. However, a peak at 12 followed by a dip at 5 o'clock would have its next peak at 10 and be out of time with the beat of the wave: the wave will not fit. So electrons circulating in atoms can only go on paths where their waves fit perfectly on the lasso. A single wave corresponds to the lowest rung of the energy ladder; two waves puts the electron on the second rung and so on.

The energies of the various waves are unique to atoms of a given element. The spectral lines that result when electrons jump from one rung to another are thus like a barcode, identifying the elements present in the Sun and other stars. It also explains the periodic regularity in chemical behaviour noticed by Mendeleev. So although we can't directly 'see' the electron waves within atoms, this hypothesis describes a host of historical phenomena and has led to a wealth of technological applications. We can therefore claim to 'know' a great deal about the inner structure of the atom, even though it is a world beyond Lilliput. **SF**



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by FRANK CLOSE

Frank is Emeritus Professor of physics at the University of Oxford

NEED TO KNOW

Five key scientific terms that will help you understand atoms

ALPHA PARTICLE

A positively charged object emitted in a form of radioactivity. Originally thought [illegible] article, hence [illegible]

SCINTILLATOR

[illegible] 20th century, Erne[illegible] therford detec[illegible] this [illegible] atomic nucleu[illegible]

ELEMENT

[illegible] ubstances are made from [illegible] ombinations of chem[illegible] [illegible] ments, which consist of [illegible] s. Examples of element [illegible]

PHOTON

[illegible]

RADIOACTIVITY

[illegible]

THE STRUCTURE OF THE PERIODIC TABLE

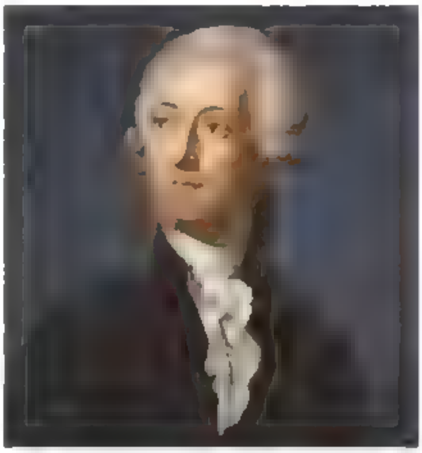
It's a familiar sight in chemistry classrooms all over the world but, as *Andrew Robinson* reveals, it took a century of scientific endeavour to work out the order and interconnectedness of the Periodic Table of Elements

The great physicist Ernest Rutherford is famously reported to have said, "All science is either physics or stamp collecting," to the irritation of subsequent generations of scientists who were not physicists. Yet when Rutherford was awarded a Nobel prize in 1908 for a physics experiment, the prize was given for chemistry. Rutherford took it with good humour, referring to his "instant transmutation from physicist to chemist."

Rutherford played a key part in developing a periodic law governing the chemical elements in the 20th century and our understanding of elements today is down to both chemistry and physics. The law was discovered in February 1869, by Dmitri Mendeleev and other chemists. Although he's regarded as a chemist, Mendeleev spent almost no time searching for the elements in his lab.

Modern matter

The modern concept of the chemical element began to emerge only in the late 18th century with the work of the French chemist, Antoine-Laurent de Lavoisier. He is generally regarded as the founder of modern chemistry from the 1770s until his death under the guillotine in 1794. Using quantitative experiments, Lavoisier defined an element empirically as a material substance that was yet to be decomposed into any more fundamental substances. In 1789, the year of the French Revolution, Lavoisier published his *Elementary Treatise on Chemistry*, in which he listed 33 simple substances, or elements. Many of these are accepted as elements today – the gases hydrogen and oxygen, metals known since antiquity, plus manganese, molybdenum and tungsten, and the non-metals carbon, sulphur and phosphorus. But other supposed chemical elements in Lavoisier's list included lime and baryta, which are now known to be chemical compounds, and light and heat, which belong in physics, not chemistry.



French chemist Antoine-Laurent de Lavoisier was regarded as the father of modern chemistry

The next step towards classifying the elements was taken by an English chemist, John Dalton, around 1803. Dalton assumed that each element consisted of a particular type of atom – an indivisible entity. Using Lavoisier's data, Dalton estimated the relative atomic weights (see 'Need to Know', page 41) of several important elements by analysing simple chemical compounds. Water appeared to be about one-eighth hydrogen and seven-eighths oxygen by weight. This led Dalton to assign an atomic weight of one to hydrogen and seven to oxygen, by assuming water's molecular formula to be HO. Although Lavoisier's measured proportions were somewhat inaccurate and Dalton's molecular formula in this particular case was erroneous (as everyone now knows), his approach was sound. The relative atomic weights of the elements would prove crucial, after further refinement, to the construction of periodic tables in the 1860s.

A German chemist, Johann Wolfgang Döbereiner, began the process. From 1817, over several years he noticed that triads of elements sharing similar chemical properties also shared a pattern in their atomic ❯

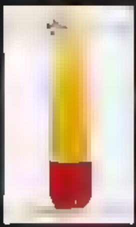
GETTY

IN A NUTSHELL

Two millennia after the ancient Greeks wrongly classified the four elements as fire, water, wind and earth, Dmitri Mendeleev uncovered underlying patterns in nature – leading to one of the most powerful tools in science

TIMELINE

1817



In triads of chemically similar elements, like chlorine, bromine (left) and iodine, **Wolfgang Döbereiner** declares the second element's atomic weight to lie midway between that of the first and third.

1858

Atomic weights are standardised by **Stanislao Cannizzaro**, using Amedeo Avogadro's 1811 hypothesis.

1869

After partially successful attempts by several chemists to detect periodicity in the atomic weights of the elements, **Dmitri Mendeleev**, while writing a chemistry textbook, introduces the basis of a successful periodic table.

1875

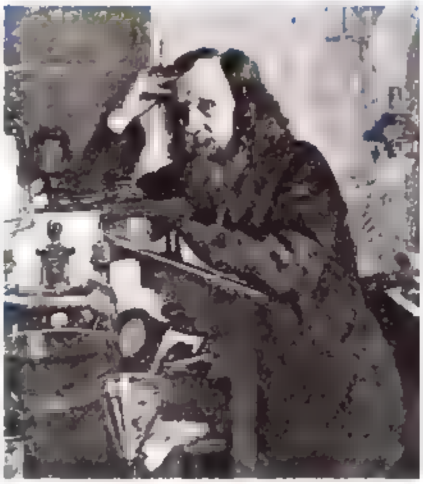
Gallium (above), the first of three hitherto unknown chemical elements predicted by Mendeleev from his periodic table, is discovered by **Paul-Émile Lecoq de Boisbaudran**. Scandium is discovered in 1879, and germanium in 1886.

1911

After bombarding gold foil with alpha particles, **Ernest Rutherford** and collaborators establish the nuclear model of the atom. **Antonius van den Broek** theorises that an element's nuclear charge determines its atomic number.

1913

By examining elements' X-ray spectra, **Henry Moseley** shows that nuclear charge and atomic number are connected; chemical properties are determined by this number, and only about 90 elements occur naturally.



Dmitri Mendeleev may have arranged the elements like a game of solitaire to create his famous table

weights. For instance, the alkali metals lithium, sodium and potassium had the respective atomic weights 7, 23 and 39. Sodium's atomic weight must therefore lie midway between those of lithium and potassium ($7 + 39 = 46$; $46 \div 2 = 23$). The same relationship held for the alkaline-earth metals calcium, strontium and barium, and for the halogens chlorine, bromine and iodine. Between 1827 and 1858, other chemists extended Döbereiner's observations beyond these triads by adding magnesium to the alkaline-earth metals and fluorine to the halogens. Oxygen, sulphur, selenium and tellurium were classified as a family; nitrogen, phosphorus, arsenic, antimony and bismuth as yet another.

Multiple approaches

In 1858, an Italian chemist called Stanislao Cannizzaro published a standardised list of atomic and molecular weights. He did so by reviving the 1811 hypothesis of his compatriot, chemist/physicist Amedeo Avogadro, concerning gases. Avogadro, unlike Dalton, had guessed that gases such as hydrogen and oxygen were composed of molecules, which were themselves composed of atoms. This meant that the molecular weight of the gas must be different from the atomic weight of its constituent element. The molecular weight depends on how many atoms of the element are contained in the molecule: two atoms in the case of oxygen. Cannizzaro's analysis formed the basis for discussion at the first international congress of chemists, held in Karlsruhe, Germany, in 1860.

Among those attending were Dmitri Mendeleev from Russia, Julius Lothar Meyer from Germany and William Odling from Britain. All three chemists, along with two others, John Newlands and Gustavus Hinrichs, and a French geologist, Alexandre-Émile Béguyer de Chancourtois, proposed different versions of the periodic table during the 1860s. They investigated patterns in atomic weights, chemical properties and, in the case of Hinrichs, atomic spectra of the 63 elements known at this time.

Mendeleev's proposal, which occurred to him while writing a Russian chemistry textbook, was the last of these six. It was published in draft form in 1869 and more fully in 1871, although it appears not to have been influenced by the five earlier proposals. All the proposals had considerable merit, but only Mendeleev's would become established. The main reason it succeeded was that between 1869 and 1871, Mendeleev had made a number of predictions of the existence of unknown elements. He labelled them with the Sanskrit word, 'eka', meaning 'one'. They included eka-aluminium, eka-boron and eka-silicon, which he predicted would have the atomic weights 68, 44 and 72, respectively. The first of them was discovered in 1875 and named gallium (atomic weight 69.7), the second in 1879 and named scandium (atomic weight 45.0), the third in 1886 and named germanium (atomic weight 72.6). Moreover, Mendeleev predicted almost all of the chemical properties of the new elements correctly.

Not all his predictions were so successful. Well before his death in 1907, new discoveries challenged his theory. In fact, current versions of the periodic table ignore three cardinal principles dear to Mendeleev: the valency, the indivisibility and the immutability of the atom.

The valency is the number of chemical bonds an atom can form with other atoms. The noble (inert) gases helium, neon, argon, krypton, radon and xenon – discovered in the 1890s by the chemist William Ramsay and the physicist Lord Rayleigh – appeared totally unreactive, with a 'forbidden' valency of zero. Today, we know some do form a few chemical compounds. The discovery of the electron in 1897

> "Mendeleev made a number of predictions of the existence of unknown elements. The first of them was discovered in 1875 and named gallium"

by the physicist JJ Thomson disproved indivisibility – the atom plainly had an inner structure. And radioactivity, discovered by the physicist Henri Becquerel in 1896 and named by the physicists/chemists Marie and Pierre Curie in 1898, showed that transmutation of elements does occur. Elements like uranium, polonium and radium all undergo radioactive decay.

By the numbers

Most serious of all the objections, though, was Mendeleev's unyielding reliance on increasing atomic weight as the chief ordering principle of his periodic table. The higher the atomic weight of an element, the later should be its position in the periodic table, he maintained. Mendeleev himself was aware of this difficulty, because he allowed one or two exceptions to this rule – notably for tellurium, which he placed earlier than iodine despite an atomic weight of 127.6 for tellurium versus 126.9 for iodine. He justified this reversal on the grounds that the atomic weights for one or both of these elements had been incorrectly determined. But his reasoning turned out to be wrong. While tellurium does indeed have a higher atomic weight than iodine, its atomic number, 52, is now known to be smaller than the atomic number of iodine, 53.

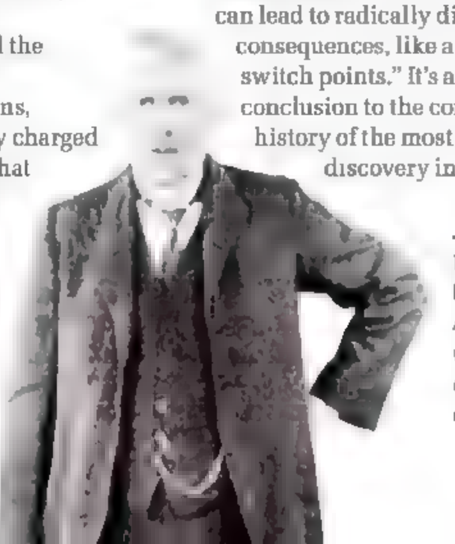
Atomic number was a concept unknown to Mendeleev. In some 19th-century periodic tables, elements were simply numbered according to increasing atomic weight. The concept owes its existence to physicists, notably the work of Rutherford and Henry Moseley between 1911 and 1914.

Rutherford discovered the atomic nucleus, with its positively charged protons, around which negatively charged electrons orbit, an idea that Niels Bohr later refined. Moseley followed a suggestion by an economist and amateur physicist, Antonius van den Broek, that the number of an element should correspond to its nuclear charge; in other words, to its number of protons. By measuring the wavelengths of characteristic X-ray spectral lines of many elements, Moseley showed that the wavelengths depended in a regular way on the element's atomic number.

It is atomic number, not atomic weight, which is the ordering principle of the many versions of the modern periodic table. The reason why atomic weight nevertheless remains a good guide to an element's properties is that increasing atomic weight generally parallels increasing atomic number, because atomic weight is determined by the protons and the neutrons in the nucleus. As the number of protons rises through the periodic table so (as a general rule) does the number of neutrons. Hence, rising atomic number and increasing atomic weight roughly correspond.

That said, the physics of the atom will never completely predict its chemical behaviour as an element. In the words of *The Periodic Table*, a celebrated collection of short stories by Primo Levi, the Italian-Jewish chemist who evaded being gassed at Auschwitz in 1944, "one must distrust the almost-the-same."

Even potassium and sodium, nearest neighbours as alkali metals in the periodic table, can behave very differently under the same circumstances: one causing an explosion, the other not. Alluding to his own narrow escape from death in the Holocaust, Levi added: "The differences can be small, but they can lead to radically different consequences, like a railroad's switch points." It's an appropriate conclusion to the convoluted history of the most profound discovery in chemistry. **SF**



Ernest Rutherford (1871-1937) revealed the structure of the atomic nucleus

by ANDREW ROBINSON

Andrew is a science writer and the author of Einstein on the Run

NEED TO KNOW

Terms you'll need to understand The Periodic Table

ATOMIC NUMBER

[illegible] ...umber of an [illegible] ...gen's atomic number is eight, gold's 79. Many elements occur in more than one form, known as isotopes [illegible] ...s of pro... [illegible] different numbers of ne... [illegible] ...on has two stable [illegible] carbon-12 (the most common) and carbon-13, and one radioactive isotope carbon-14.

ATOMIC WEIGHT

[illegible] ...n as relative atomic [illegible] ...omic weight of an element is the ratio of th... [illegible] ...atom of [illegible] ...fth th... [illegible]

ELEMENT

[illegible] ...element [illegible] ...gen or go... [illegible] ...d into [illegible] ...nces by chemical [illegible] The atoms of a given element all have the same [illegible] number of each element [illegible]

COMPOUND

A chemical compound is a substance that is composed [illegible] ...o or more different [illegible] chemica... [illegible]

UNDERSTANDING QUANTUM PHYSICS

Even Nobel Prize-winning physicists are baffled by this tricky subject. But *Dr John Gribbin* is here to reveal why quantum physics is relevant to all our lives

Q What is quantum physics for?

A Quantum physics may seem like a pretty esoteric topic with no everyday practical value, but that's far from the case. Quantum physics is the science you need to understand the behaviour of atoms, electrons and light. It therefore underpins the workings of microchips and lasers, among many other things. The chemical bonds that hold strands of DNA together and which enable the double-stranded molecules of the famous helix to unzip and make copies of themselves, operate purely in accordance with the laws of quantum physics. Quantum physics is the science of life: it doesn't get much more basic than that!

Q Wave, particle or both?

A The understanding of physics that scientists had reached by the end of the 19th century is now called 'classical physics'. It describes the behaviour of the material world in terms of the laws discovered by Isaac Newton and it describes the behaviour of light and other electromagnetic radiation (everything from radio waves to gamma rays) in terms of the wave equations of James Clerk Maxwell.

Crucially, in the world of classical physics, waves are waves and particles are particles. They interact with one another – as when an electrically charged, jiggling electron emits radio waves – but they always retain their identity. Even the General Theory of Relativity (like its simpler cousin the Special Theory of Relativity) counts as a classical theory, because it retains this distinction between waves and particles, and preserves the idea that changes happen continuously.

Quantum physics overturns all of that. The first clue that something other than classical physics was needed came when Max Planck found that he could only explain some aspects of the behaviour of light (such as the nature of so-called black body radiation – see 'Timeline' on page 46) by treating light as being made up of particles, not a continuous wave. But other experiments still showed light behaving as a wave. Then it was discovered that electrons, which classical physics said were particles, behaved in some circumstances as if they were waves. Wave-particle duality, as it became known, lies at the heart of quantum physics.

When Max Planck suggested that light was made up of particles, he completely overturned classical physics

GETTY

Q Does quantum theory rule?

A Wave-particle duality is not the whole story of the split between classical physics and quantum physics. In the world of classical physics, a particle such as an electron has a definite position in space and is moving in a definite direction. As long as you make allowance for all the forces it encounters along the way, you can calculate everything that will ever happen to it. This applies to all particles. The classical world is said to be 'deterministic' because once you know where everything is and where it is going, you can work out the entire future and the entire past. Both are determined by the way things are ➲

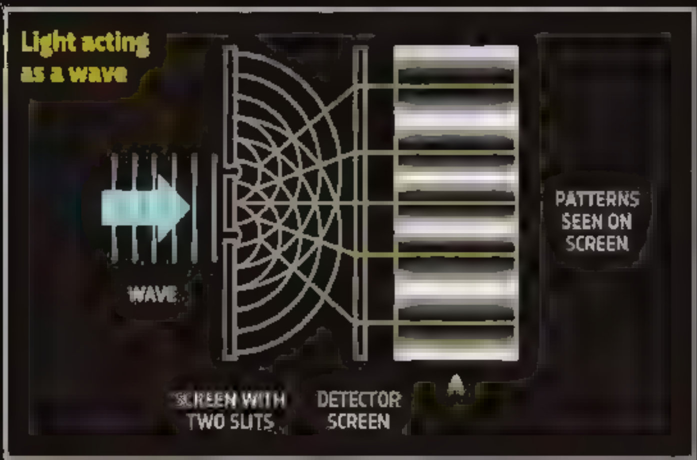
THE KEY EXPERIMENT

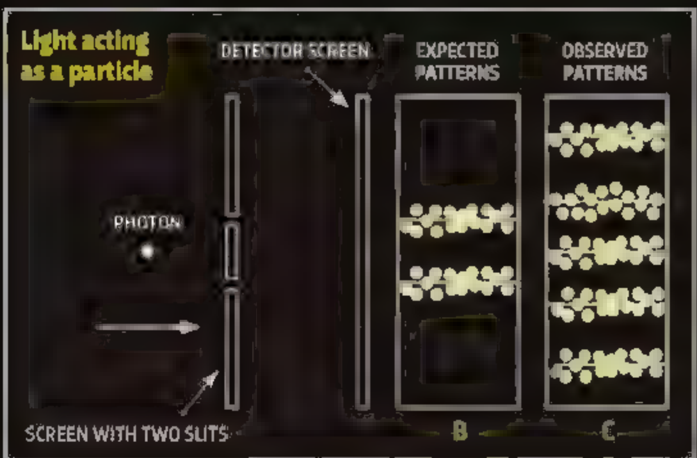
Proof that light can be a wave or a particle

In the 18th century, debate raged as to whether light was a wave or a particle. But in 1803, English scientist Thomas Young showed that, when light is passed through two slits onto a backboard, an interference pattern appears. This is similar to what's seen when two sets of similarly generated waves collide in water (A). Light, he deduced, must be a wave. In the early 20th century, however, Einstein and others demonstrated that light can also be seen as a stream of particles – photons.

This is where things get tricky. When individual particles are sent one at a time through a double slit, as in Young's experiment, they should 'pile up' in two bands (B). Photons don't, though: even if you send photons through the double slit individually, an interference pattern is observed (C). Just to complicate matters, if you monitor which slit each photon is going through, the interference patterns are replaced by two bands.

The same applies to other fundamental particles, such as electrons. If that sounds a bit mind-blowing, welcome to the world of quantum physics, where 'wave-particle duality' is commonplace and where the mere act of observing can affect the outcome of an experiment.





now, which doesn't leave very much room for free will. This is sometimes called 'Newton's Clockwork Universe'.

But according to quantum physics, an electron is never located at a precise place (because of its wave nature), and it is never sure where it is going. This is the 'uncertainty principle' discovered by Werner Heisenberg, who found that there is a trade-off. Quantum objects can either have a relatively well-defined position and a poorly defined direction, or a well-defined direction and a poorly defined position. But they can't have both. It's the price of free will.

This ties in with another concept that's key to quantum physics: probability. You can never say precisely where a quantum entity is or where it is going, but you can use quantum physics rules to work out probabilities, such as the probability that an electron will follow a certain trajectory, or the probability that a sample of radioactive material will decay and spit out a particle within a certain time.

Q What is a quantum?

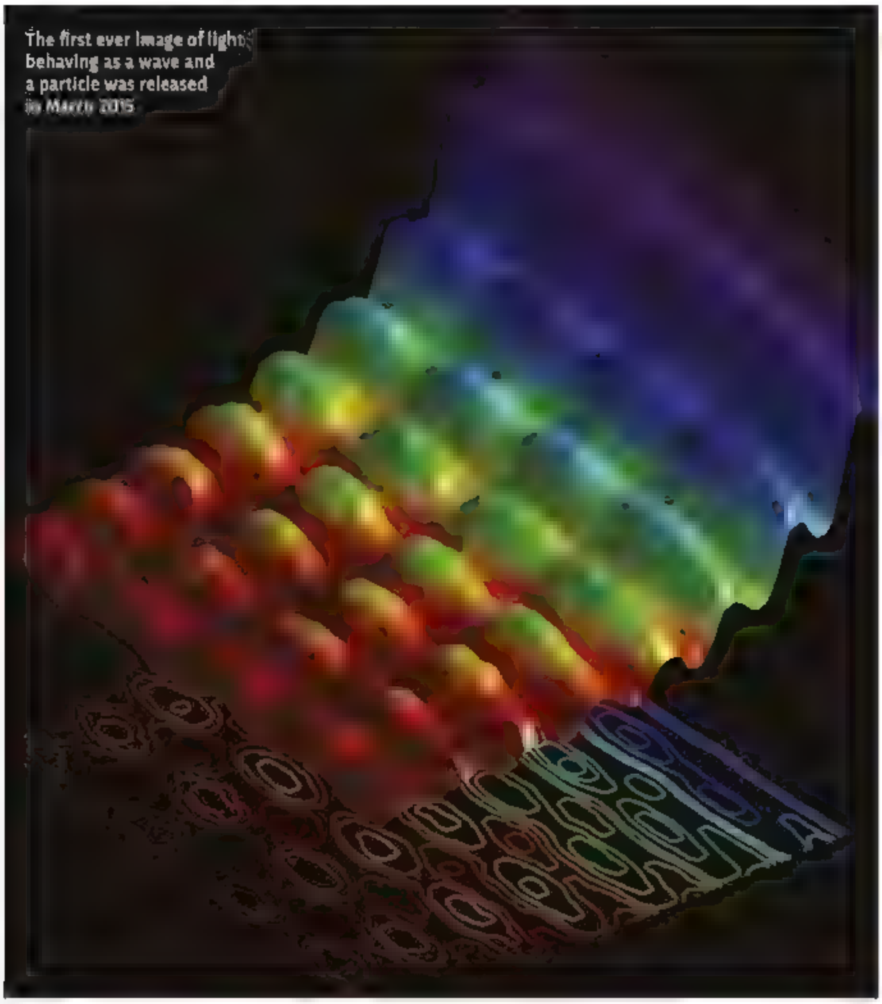
A A quantum is the smallest amount of something that it is possible to have. The smallest amount of light you can have, for example, is a particle called a photon. If you have a bright light, there are many photons streaming outwards. But as you turn the light down, there are fewer and fewer photons. Eventually, there are so few photons that they can be detected one at a time.

Astronomers see this happening when they build up images of very faint objects using long exposures of charge-coupled devices (CCDs). When atoms emit light, they do so by rearranging their electrons to radiate energy. Like a ball bouncing down a staircase, the electron jumps from one energy level to another inside the atom and a photon is emitted. This jump is known as a quantum leap.

A quantum leap is the smallest change it is possible to make – something to remember next time you see the term used in advertising.

In one tweet...

Quantum physics gives us free will. Without it you would have no choice about anything. It explains what life is and how your phone works.



The first ever image of light behaving as a wave and a particle was released in March 2015

D-WAVE

Could this be the first quantum computer? [illegible] urers D-Wave [illegible] vealed [illegible] w it works [illegible] aim is to develop computer [illegible] n the superposition idea of [illegible] n physics. These quantum [illegible] make classical [illegible]

Q Can we see quantum effects?

A The definitive demonstration of quantum effects at work was carried out by a Japanese team in the 1980s. They took the classical experiment that 'proves' light is a wave and adapted it to electrons.

The traditional experiment involves sending a beam of light through two slits in a cardboard screen to make a pattern on another screen on the far side. Like ripples on a pond, the waves started to spread out from the two slits and interfered with one another to make the distinctive pattern. In their variation on the theme, the Japanese team fired electrons, one at a time, through an equivalent setup onto a screen like a television screen, where each electron made a single spot as it arrived, showing that it was a particle.

But as hundreds of electrons were fired through the experiment, one after another, the pattern of spots that built up was an interference pattern, proving that electrons are waves.

Don't worry if you find your mind boggled by this. The physicist Richard Feynman used to say that "nobody understands quantum physics", and he had won a Nobel Prize for it.

Q Are there practical applications?

A Applied quantum physics is everywhere around us. Computer chips, including the ones in your smartphone, are designed using quantum physics and operate on quantum principles. The lasers used to read Blu-ray discs operate on quantum principles that were first worked out by Albert Einstein 100 years ago.

D-WAVE SYSTEMS, NASA, AMES

NEED TO KNOW

Understand quar physics with these terr

DIFFRACTION

DUALITY

ENERGY LEVEL

QUANTUM LEA

SUPERPOSITION

Physicists have developed tools known as superconducting quantum interference devices, or SQUIDs, in which electron waves travel around a ring of metal about the size of a wedding ring. SQUIDs are supersensitive detectors of magnetic fields and are used in many different applications, including the MRI scanners that allow doctors to 'see' inside the human body.

The most exciting application of quantum physics is in the new field of quantum computing. Ordinary computers are based on switches that can be either on or off (0 or 1); in contrast, a quantum computer has switches that can be both on and off at the same time. This is a so-called superposition, which makes the computer immensely more powerful.

Q How does quantum physics explain the Sun's energy?

A Stars like the Sun release energy as a result of a process called nuclear fusion. At its simplest, inside the Sun two protons (hydrogen nuclei) come together and fuse, then combine with other particles to make nuclei of helium. The helium has less mass than the particles that went into it, so energy is released in line with Einstein's famous equation, $E=mc^2$. Astronomers are able to figure out how hot the interior of the Sun must be in order to hold itself up against gravity.

But this then led to a puzzle. Because protons are positively charged, they repel each other and have to be moving very fast before they will collide and stick together. Classical physics said that the interior of the Sun is not hot enough for this to happen. Quantum physics provided the explanation. When two protons are close together, but not close enough to touch according to classical theory, quantum uncertainty means that there is a probability that they might touch. Another way of understanding this is to think of the protons as waves, reaching out to each other. The result is that the protons can fuse by tunnelling through the barrier of classical electrical repulsion.

Q What is antimatter?

A One of the strangest predictions of quantum physics is that for every type of particle, there should

SCIENCE & SOCIETY, GETTY X2

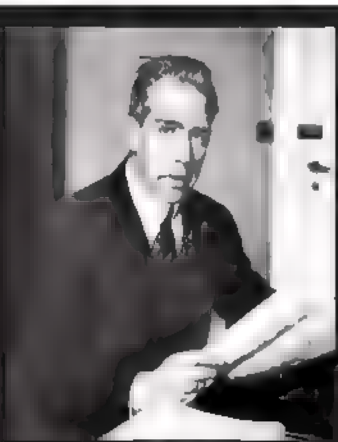
TIMELINE

1900

German physicist Max Planck discovers that black body radiation can be explained if light is emitted in packets of energy, now called photons. This conflicts with the accepted idea that light is a wave.

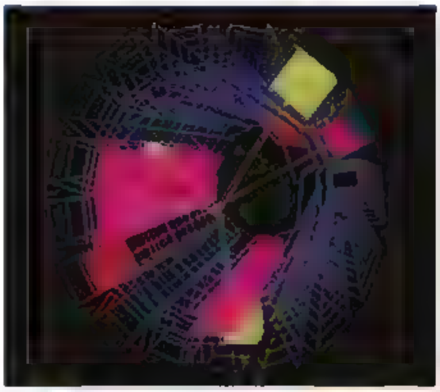
1905

German physicist Albert Einstein explains the photoelectric effect, in which light falling on a metal surface makes photoelectrons jump out of the surface.



1913

Danish physicist Niels Bohr explains the spectrum of light radiated by atoms in terms of electrons jumping between fixed energy levels, like steps on a staircase, inside the atom. This is the 'quantum leap'.



Clockwise from top left: model of a matter-antimatter annihilation event; production of a matter particle, along with its corresponding antimatter; a researcher adjusts a NanoSQUID device that changes temperature when it's hit by a photon

be an antiparticle that has its key properties reversed. The electron, for example, has a negative charge, while its antiparticle, the positron, has a positive charge.

The physicist Paul Dirac was the first person to take this seriously, but when he published the idea in the 1920s he cautiously suggested that the required positive particle might be the proton, the only other particle known at the time. But in 1932 the physicist Carl Anderson discovered the tracks of positively charged particles with the same mass as electrons in a device known as a cloud chamber. This breakthrough earned him a Nobel Prize.

Dirac had been more correct than he had realised. It turns out that particle-antiparticle pairs (such as an electron and a positron) can be made out of pure energy in line with Einstein's equation, but when a particle and its antiparticle meet they annihilate each other in a puff of gamma rays. SF

by DR JOHN GRIBBIN

Dr Gribbin is a science writer and Visiting Fellow in astronomy at the University of Sussex

CERN, SCIENCE PHOTO LIBRARY X4, GETTY

1927

US physicist Clinton Davisson and UK physicist George Paget Thomson (above) share a Nobel Prize for independently discovering that electrons can be diffracted like waves, confirming the reality of wave-particle duality.

1932

While studying cosmic ray tracks, US physicist Carl Anderson, sees the trace of a particle like an electron but with a positive charge. It is the positron, an antiparticle.

1985

David Deutsch publishes a paper pointing out the possibility of making a true quantum computer. He predicts that they will carry out certain tasks much faster than a conventional computer can.

"For every type of particle, there is an antiparticle that has its key properties reversed"

Each eye of a damselfly is made up of thousands of tiny 'facets', which can detect movement up to 15m away.

PHOTO: MIROSLAV SWIETEK/SOLENT NEWS

THE FUNDAMENTALS OF LIFE

THE ORIGIN OF LIFE

There are millions of species alive on Earth today. But how did life get started in the first place? *Tom Ireland* travels back through four billion years of history to find out

Q How long ago did life get started on Earth?

A Around four billion years ago, when the Earth was still partially molten and under heavy bombardment from meteors, the very first life-like systems appeared. Somehow, chemicals developed life-like properties – using matter and energy from the hellish environment to make more of themselves. Origin-of-life researchers are still trying to work out exactly how, during this period, chemistry suddenly became biology.

Once basic biological systems formed, life never looked back, evolving into the two enormously diverse groups of microbes now known as bacteria and archaea. A merger between two of these ancient cell types, billions of years later, is thought to have given rise to more complex, multicellular organisms – including us, and all the plants, fungi and animals that ever lived.

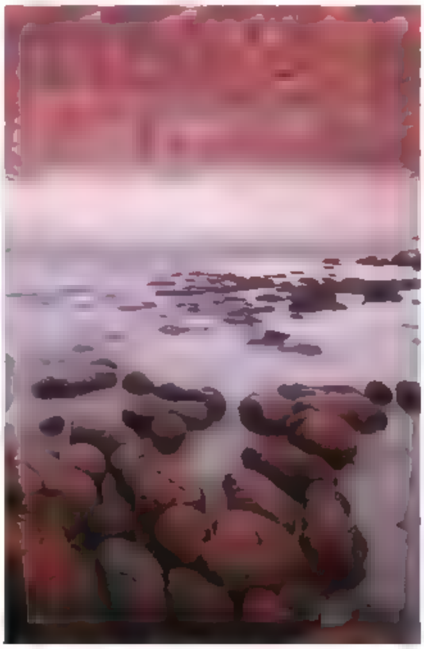
Q How exactly did life on Earth begin?

A Unfortunately, there is no consensus or standard model to explain how life started on Earth. However, most theories are based on the idea that at some point early in the planet's history, chemicals developed characteristics that are found in all living cells today – the ability to self-replicate, for example, or to produce other useful biological molecules.

Once such biological characteristics emerged, a sort of 'chemical evolution' was set in motion: chemicals made copies of themselves, some emerging with variations that made them either more or less efficient, or helped them cooperate with others. The variants that worked best made more copies of themselves, while the others were outcompeted for raw materials.

Over billions of generations, more complex variations emerged, with the basic molecular processes of life enclosed within a membrane. These cell-like structures were essentially the first microbial cells, from which all life evolved.

More fanciful theories suggest that life on Earth was 'seeded' by ancient microbes falling from space.



Stromatolites, like these in Australia, formed from ancient microbes up to 3.5 billion years ago

Q What is the earliest evidence of life on Earth?

A The oldest cells ever found are fossilised in rocks dated to around 3-3.4 billion years ago. These early cells look a bit like cyanobacteria, which is still abundant today. They were likely to have been thermophiles, meaning they liked hot places, and autotrophs, meaning they made their own complex organic compounds from simple chemicals. Further back in time, there must have been an older type of organism from which these cells evolved.

Other evidence of ancient life can be seen in the form of stromatolites – rocky structures formed from the gritty deposits of vast sheets of ancient microbes floating in the sea. Some of these, found in Western Australia, are thought to be up to 3.5 billion years

GETTY D KELLEY/M ELEND/UNIVERSITY OF WASHINGTON

Our most ancient ancestor could be a porous rock. Some scientists believe conditions in deep-sea alkaline vents would have encouraged metabolic-style reactions.

"Life is often said to have started spontaneously in a 'primordial soup' – a sort of chemical stock formed in the pools and puddles of early Earth"

old, but little is known about the organisms that made them.

The oldest evidence of life on Earth is mysterious traces of a certain isotope of carbon, which researchers think must have been produced by a living organism. Some of this graphite, also found in Western Australia, is thought to have formed around 4.1 billion years ago. This is almost as old as the oldest rocks ever found on Earth, suggesting life may have appeared surprisingly soon after the planet formed.

But what left these tantalising traces of life? Here the trail goes cold. The theory of how life began, from the innate chemistry of early Earth to those early cells, is a puzzle that remains unsolved.

Q Why are there still so many unanswered questions?

A As well as there being no clear evidence to examine, at the heart of the problem is a paradox. To make the complex biological molecules required for life normally requires other biological molecules. How could any of these intricate molecules be made when biological systems did not exist to make them?

DNA, for example, cannot form by some sort of chemical accident – to make it requires specific enzymes. But to make those enzymes requires the precise instructions carried by DNA.

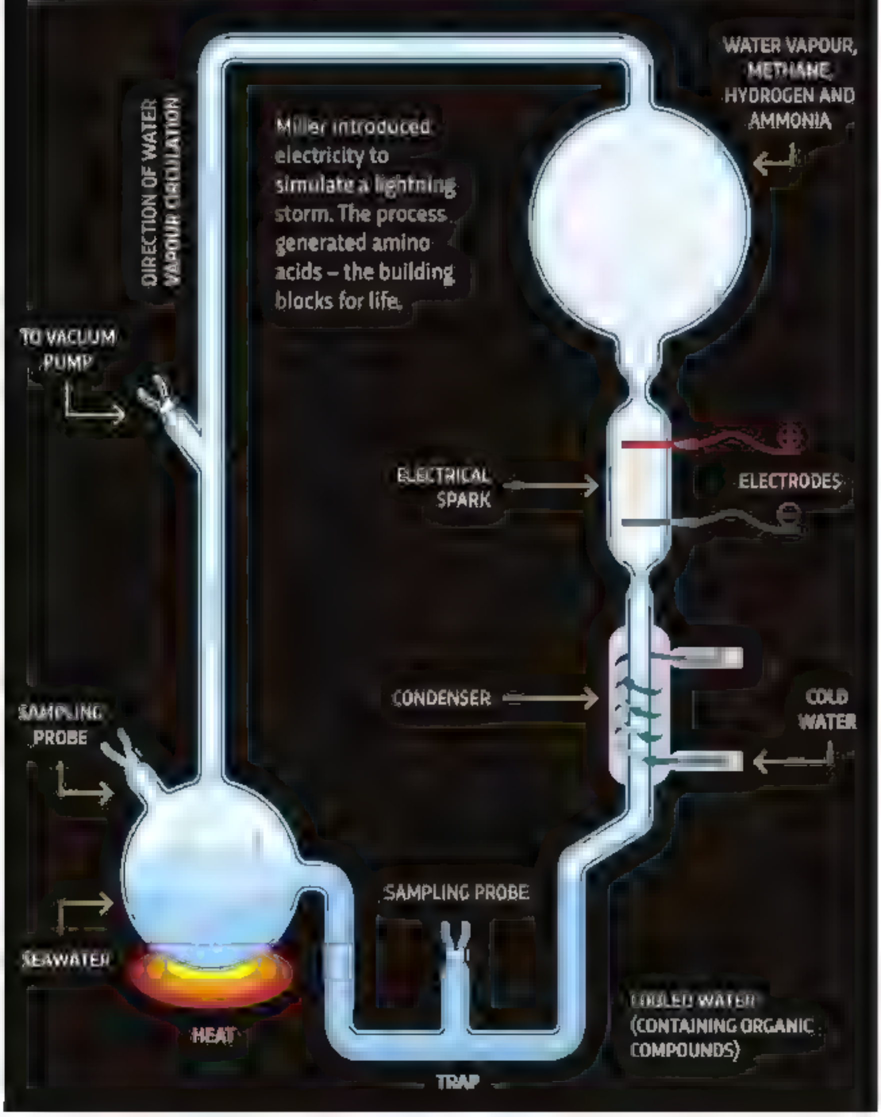
There are other fundamental problems too – even if complex organic molecules like enzymes and DNA did arise spontaneously, how and why did they begin to cooperate as a system? And how did early life manage to create large organic molecules without the complex energy systems that drive the process in modern cells?

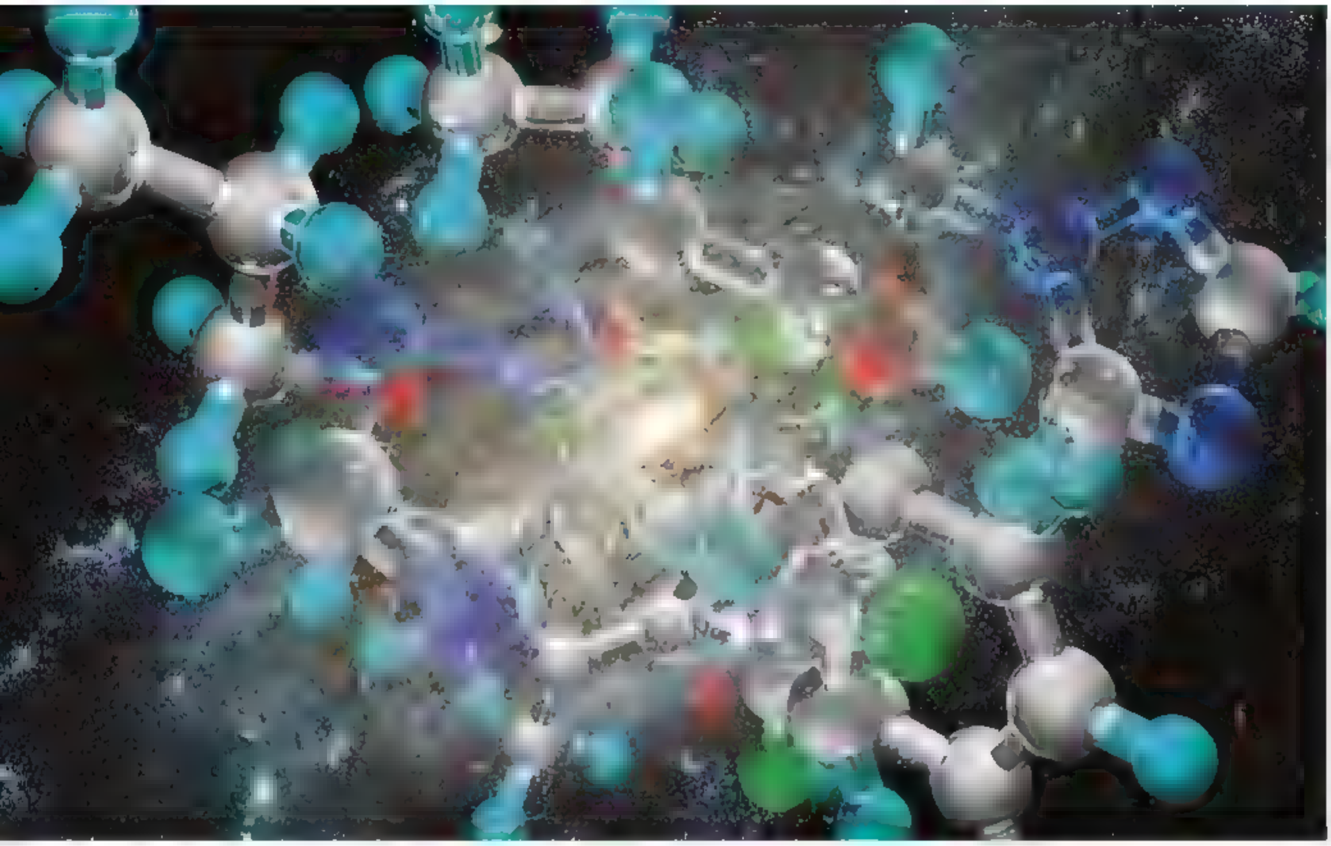
Q What exactly is a 'primordial soup'?

A Life is often said to have started spontaneously in a 'primordial soup' – a sort of chemical stock formed in the pools and puddles of early Earth. Charles Darwin once wrote a letter to a friend in which he speculated whether life could have originated in "some warm little pond somewhere" and scientists such as JBS Haldane and Alexander Oparin (who coined the phrase 'primordial soup') developed the theory in the 1920s. Both said that various chemical compounds could accumulate and become concentrated in locations where hydration and drying regularly occur, such as shorelines, rocky pools or oceanic vents. Cycles of hydration and drying, plus energy from magma,

THE KEY EXPERIMENT

Scientist Stanley Miller combined seawater and various gases together to replicate the ocean and the atmosphere





Computer visualisation of biomolecules in the Universe

ultraviolet light or lightning, could be conducive to the production of complex organic molecules, they said. Finally, at some point, fat-like molecules could have formed an 'oily film' on the soup that enclosed important molecules within bubbles, forming the first cell-like units.

For decades, however, there was very little evidence to support this idea. It appeared that the essential molecules of life – proteins, fat-based cell membranes, and DNA – were only found in living organisms and could not form without the molecular machinery contained inside cells.

In 1952, a young scientist named Stanley Miller put water, methane, hydrogen and ammonia together, and frazzled it with thousands of volts to emulate the fierce electrical storms that would have been a feature of Earth's turbulent atmosphere at the time life first appeared (see 'The Key Experiment', left).

Within a few days, the mixture had turned into a rich, brown mix of chemicals and analysis found that amino acids – the building blocks of proteins – had formed spontaneously.

The experiment was key in supporting the view that life could arise from simple chemicals on the surface of the Earth. Modern analysis has since found that all 22 of the essential amino acids required for life can be made like this. Scientists have also since made other important biological chemicals in similar ways, such as nucleotides, the building blocks of DNA.

So did life form in the primordial soup? Well, this approach only gets us so far. Even with a 'soup' stocked with the ingredients of life, such as amino acids and nucleotides, it's still enormously difficult to get these ingredients to form very complex biochemicals, such as proteins or DNA. And it's even more difficult to make versions of those molecules with meaningful biological functions.

Q Could life have begun anywhere else?

A Another theory gaining credibility is the idea that life began in deep-sea hydrothermal vents. At the time of life's origin, the seawater was acidic and positively charged. In contrast, the vents ejected negatively charged, alkaline substances.

These fissures in the Earth's crust, where alkaline minerals reacted with acidic seawater, created tiny pores in rocks, which appear to concentrate chemicals produced by other reactions in the vent.

Iron- and sulphur-based minerals in the vents could have helped catalyse reactions, just like iron- and sulphur-based proteins do in modern cells. Today, such vents often host complex microbial communities, fuelled by the chemicals dissolved in the vent fluids.

The most exciting aspect of this theory, however, is the complex chemistry occurring between the inside and the outside of the microscopic pores. This could create what is known as a 'proton gradient' – an absolutely key part of the way all organisms store energy and use it to build complex molecules.

The final stage in the theory again involves the production of fatty molecules, which can spontaneously form bubble-like, cell-like spheres. Having been produced in the chemical froth, some of these bubbles could have enclosed self-replicating sets of molecules – forming the very first organic protocells.

Q Could life have arrived on Earth from space?

A The idea that life originated in space, known as panspermia, is not as wacky as it sounds. Scientists have found lots of unexpectedly complex molecules, such as amino acids or small components of DNA, nestled on comets or meteorites that have crashed to Earth. ●

SCIENCE PHOTO LIBRARY

In one tweet...

Life may have started 4.1bn years ago, not long after the Earth formed. But how did it begin? It's one of science's greatest questions.

Most scientists say that these chemicals, at best, simply 'stocked the soup'. There is no evidence that cells or more complex biological molecules, such as protein or DNA, have travelled to Earth from space.

Q So what was the first biological molecule?

A The holy grail of origin-of-life research is understanding which chemicals developed life-like properties first and how they began to work together.

The fact that DNA carries the instructions for life suggests it was central to early life. But researchers are increasingly focused on another molecule, RNA, as potentially the first chemical to come to life. RNA is similar in structure to DNA and performs lots of key functions in cells, from making proteins to translating and communicating the genetic code. 'RNA world' is the name given to the theory that before DNA, self-replicating RNA units began to proliferate and evolved complexity.

Researchers making random sequences of RNA have found that some can form complex shapes, which help them perform various functions, like being a catalyst for the production of other molecules. And scientists have created an RNA molecule (R3C) that helps to create more of itself. This 'protogene' lends support to the idea that chemicals can develop life-like properties such as self-replication.

Other theories suggest that life began with a much simpler version of DNA and RNA – one that was easier to form from the chemicals of early Earth. This then evolved into the amazingly robust and efficient information-carrying molecules that we see today.

Prof Nicholas Hud, from the NASA-funded Centre for Chemical Evolution, believes there may have been several biological molecules coexisting at one point and 'life' as we know it started when they began to cooperate. "I don't believe that there was one first self-replicating molecule. I think we are descendants of the polymers that started to work together. Four types of polymer essentially form most of the metabolism of life: lipid membranes, polysaccharides [sugars], proteins and nucleic acids. These are the survivors of perhaps many different polymers."

Q Are there any other theories that are considered possible?

A There are dozens more theories. Many are based on conditions that might have helped concentrate important biochemicals and protect them from degradation, such as the 'clay theory', which suggests crystals in clay helped arrange organic molecules into organised patterns.

Others attempt to deduce the order in which the molecules of life formed and began to cooperate. One example is the 'lipid world' theory, which suggests that membrane-like bubbles of fatty molecules were the first step towards cellular life. Although these wouldn't be information carrying units, like RNA or DNA, they may have been able to produce more of themselves and RNA might then have formed more easily within them.

Q Will we ever find a satisfactory answer?

A Scientists working on this problem still disagree on the fundamentals. Speaking to origin-of-life researchers at times sounds like they are moving further away from a consensus, rather than closer.

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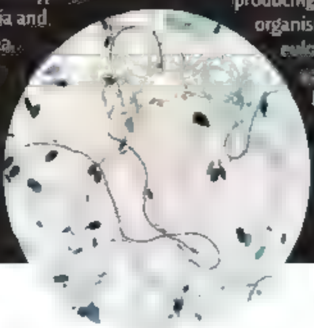
TIMELINE

3.8-4.5 billion YEARS AGO

First living organisms appear. Specks of graphite, thought to be produced by early life, have been dated to 4.1 billion years ago – as old as the oldest rocks.

3-3.5 billion YEARS AGO

The oldest evidence of actual microbial cells dates back to around three billion years ago. These were similar to cyanobacteria (below). The last known common ancestor of all life on Earth lived in this period, just before cells split into two main types: bacteria and archaea.

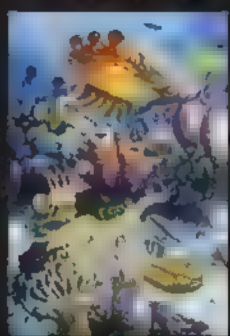


2-2.5 billion YEARS AGO

Evidence of oxygen in the atmosphere suggests an abundance of oxygen-producing, photosynthetic organisms. The first eukaryotic cells appear, thought to be the result of one cell enslaving another as an energy source.

580 million YEARS AGO

Multicellular life on Earth starts flourishing. The relatively short period during which many animals first appeared is known as the 'Cambrian explosion'. Pictured are some creatures that lived in this period.



2-3 million YEARS AGO

The first humans or human-like beings appear on Earth.

Researchers are increasingly investigating RNA as a key candidate for helping life to evolve

ISTOCK, SCIENCE PHOTO LIBRARY

Dr Nick Lane, a biochemist and author of the origin-of-life book *The Vital Question*, says the problem is even harder to solve than those posed by theoretical physics. "We are not even in the position of the physicists, where everyone at least agreed what the question was and could build a huge machine like CERN to look for the answer. We are still miles away from that agreement."

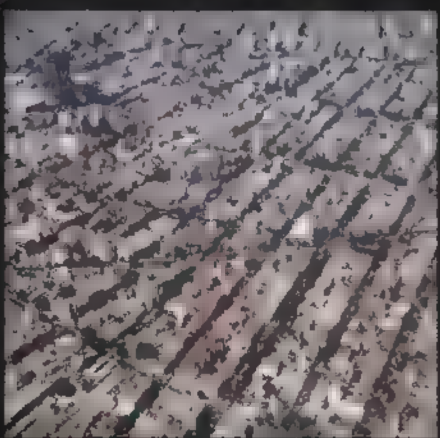
However, despite the lack of a unifying theory, many scientists remain confident that a satisfactory solution is achievable. Increasingly, scientists are using computer modelling to investigate how certain mixtures of molecules might behave over time – an advance that could help speed up progress in this area. "I don't think I'm that far away..." says Dr Lane, semi-seriously.

"The key message is that the nuts and bolts of all life is almost identical," says Dr Matthew Powner, a chemist studying the origin of life at University College London. "The difference between us and a tree seems obvious, but people often don't understand how similar the biochemistry that it's all built from is, using very few chemical species. Eight nucleotides, 20 amino acids and a few lipids, and you don't need much else."

The overall solution may not have been solved yet, but each and every life-like molecule that emerges from a laboratory is another piece of the puzzle found. As broadcaster and geneticist Dr Adam Rutherford concludes in his book *Creation: The Origin of Life*, "That first time had millions of years, whereas scientists have made these replicators in a decade... In all origin-of-life studies it is important to remember that we know the answer: life is the answer. The question is finding a believable route to get there." **SF**

Present day

There are estimated to be at least 10 million species of organism living on Earth today, but the vast majority are still unknown to scientists. The human population is over seven billion, and mankind is now exploring space for signs of other life.



by TOM IRELAND

Tom is a journalist and managing editor at the Royal Society of Biology

NEED TO KNOW

Key terms to help you understand the origin of life

ABIOGENESIS

...he technical term for life originating from non-liv... matter, such as s... chemicals. The opp... ...enesis, means living matter ...ng from othe...

RNA WORLD

...many important functions in al... ...ng cells. Scientists have ...hown that RNA can ...taneously form a ...eplicating molecule ...ing Earth was once populated by simple ...eplicating RN...

PROTON GRADIENT

Cells can only function properly ...eated by complex ...reactions, which generate a difference in ...hemical charges in diffe... ...rts of the c... ...s a proton gradien...

LUCA

...rsal Common ...e ancient ...f all life on...

PANSPERMIA

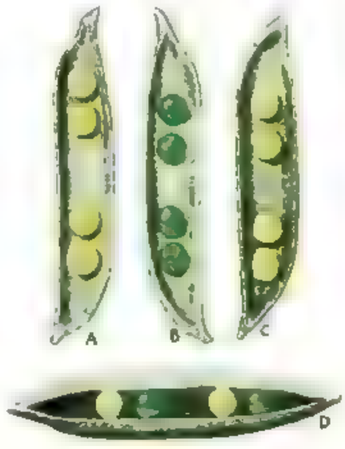
THE STRUCTURE OF DNA

Before the gene-carrying molecule DNA was discovered, we had no idea of the mechanics of life. *Katherine Nightingale* reveals how describing its double-helix form was one of the greatest scientific achievements

The year is 1869 and a young researcher is toiling away in a laboratory in an old castle in Germany, on course to make a remarkable discovery. The lab studies the composition of cells and Friedrich Miescher is analysing white blood cells, which he extracts from the pus in a local clinic's discarded bandages. Having exhausted his efforts in classifying the cell's proteins, Miescher turns his attention to another substance in his samples. He finds it odd – an acid that contains phosphorus – and declares he has discovered a completely new type of substance. Nuclein, or DNA as we now call it, has been found.

Like any good sceptical scientist, Miescher's boss Felix Hoppe-Seyler is wary and waits to repeat the experiments before, two years later, allowing publication. But this delay would turn out to be negligible; it was many more decades before scientists saw the importance of DNA. Misecher went on to find DNA in a variety of cells, but even he couldn't believe that just one substance generated the enormous diversity of life. As late as the 1940s, most scientists thought that proteins – large biological molecules that come in all shapes and sizes – were the only substances complex enough to be the agents of heredity.

Chromosomes, the coils of DNA and protein that contain genes, had first been spotted in cells in the early 1840s. Later that century, researchers saw them double in number and then halve again into separate 'daughter' cells during cell division. In 1865, the Austrian monk Gregor Mendel used pea plants to explore theories on genetic inheritance, proposing that characteristics are inherited in discrete units. When his research was rediscovered in the early 1900s, a flurry of work determined that these units, or genes, must be in chromosomes. But what were they made of: DNA or protein? And what did they look like?



Gregor Mendel cross-bred different coloured peas in some of the earliest experiments into heredity

A German doctor named Albrecht Kossel took some of the first steps towards finding out. Working under Hoppe-Seyler in the late 1800s, he discovered DNA's 'bases' and named them thymine (T), adenine (A), cytosine (C) and guanine (G). This work was continued by Phoebus Levene, a Lithuanian researcher driven to New York in the early 1890s because of anti-Semitism in his adopted home of St Petersburg.

The units of DNA

For three decades from the mid-1890s, Levene studied the structure of DNA, identifying its other components: a sugar called deoxyribose and phosphate groups. He also discovered that DNA is made up of units he called nucleotides. Each of these is made up of a sugar, phosphate group and base, and are linked by bonds between the phosphate groups of one nucleotide and the sugar of the next.

But this was as far as Levene's correct findings went. He thought that each DNA molecule contained only four nucleotides, one with each type of base, linked together in a ring he called a 'tetranucleotide'.

Levene's tetranucleotides were too simple to carry a genetic code and ➲

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The double helix of DNA: nature's elegant solution to the blueprint of life

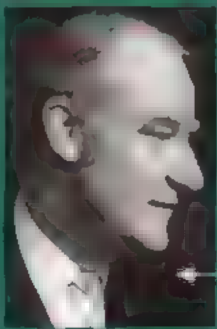
IN A NUTSHELL

The key to all life on Earth: a simple molecule known as DNA found in every cell of your body. It took several breakthroughs to fully understand the extent of its role in biology, a discovery that triggered a scientific revolution

CAST OF CHARACTERS

It took the ef[illegible] DNA

WILLIAM ASTBURY (1898-1961) was a British molecular biologist and physicist who spent much of his working life in Leeds. His work focused originally on the [illegible] proteins in textiles but along with his PhD student Florence Bell, he took the first X-ray photographs of DNA in 1937



FRANCIS CRICK (1916-2004) was born near Northampton to the owner of a shoe factory and became a British biophysicist and molecular biologist. After co-discovering the structure of DNA he went on to determine how DNA codes for proteins before venturing into neuroscience

MAURICE WILKINS (1916-2004) was a British physicist and molecular biologist who was born in New Zealand. As well as his DNA research he worked in fields such as radar and microscopy. He remained at King's College until his retirement in 1981

ROSALIND FRANKLIN (1920-1958) was born in London to a rich Jewish family. The X-ray crystallographer and biophysicist provided much of the experimental evidence for the structure of [illegible] switching her focus to viruses. She died of [illegible] at the age of 3[illegible]

JAMES WATSON (1928-) is an American geneticist and molecular biologist born in [illegible]o, who gained [illegible] DNA structure in Cambridge [illegible] he worked at Harvard University and then the Cold Spring Harbor Laboratory until he ret[illegible]

so reinforced the idea that proteins must be the hereditary agent. Revealing DNA's hidden complexity was going to require a closer look. While Levene was unravelling the complexities of DNA in New York, across the Atlantic a father-and-son team was establishing a technique that would prove crucial to determining DNA's structure.

William Henry Bragg, a physicist at the University of Leeds, and his son William Lawrence Bragg, a researcher at the Cavendish Laboratory in Cambridge, laid the foundations for the field of X-ray crystallography between 1912 and 1914. They were inspired by the work of Max von Laue, who discovered in 1912 that X-rays bend when they pass through crystals, substances with highly ordered structures.

The younger Bragg reasoned that, because they have ordered patterns of atoms, the way that the X-rays bend through crystals would reveal something about their structure. His more practically minded father built the first X-ray spectrometer – a device for shooting a narrow beam of X-rays at substances – and together they tested the theory on salt crystals.

Bragg's Law

In these experiments, the Braggs placed a photographic plate behind the crystal, onto which the scattered X-rays would produce a characteristic pattern. William Lawrence Bragg came up with an equation, known as Bragg's Law, that allowed them to work backwards from the patterns to deduce the crystal's structure. The pair won a Nobel Prize in 1915.

One of the first groups to apply this technique to biological molecules was headed by William Astbury, who began working at the University of Leeds in 1928, having studied under William Henry Bragg at the Royal Institution. In 1937, Astbury was sent samples of calf DNA by Swedish researcher Torbjörn Caspersson. A few years previously, Caspersson had shown that DNA is a polymer – a long chain of nucleotides – rather than the short lengths Levene had suggested.

OREGON STATE UNIVERSITY, ALAMY X2, GETTY, COLD SPRING HARBOR LABORATORY

> "They created conditions in which only DNA (not protein) could be transferred, hence determining that only DNA could pass on traits"

Astbury's PhD student, Florence Bell, took the first of hundreds of X-ray diffraction pictures of DNA that year. The fact that it produced a pattern at all suggested that DNA had a 'solvable' structure. Astbury and Bell's pictures look like smears compared to the clear images that Rosalind Franklin was able to produce in the early 1950s, but their pictures did reveal one crucial fact: the distance between the bases in the DNA molecule.

In 1938, Astbury used the images he and Bell produced to propose a structure for DNA in which the bases are stacked on top of each other, but the pictures weren't detailed enough for him to get further.

Clues in bacteria

Meanwhile, back in the US, a medical researcher named Oswald Avery was busy refining a 1928 experiment by a British microbiologist called Fred Griffith. He had shown that it was possible to make harmless bacteria and their progeny dangerous by mixing them with virulent bacteria, suggesting that something was being transferred from the virulent to harmless bacteria. Avery and his colleagues deliberately created conditions in which only DNA – not protein – could be transferred. In this way, they determined that only DNA could pass on traits. Though many would refuse to believe it, DNA had been strongly implicated as the carrier of inheritance and science had the tools to find out what it looked like. The stage was set for the race to find the structure of DNA in the 1950s – only not everyone knew it was a race.

DNA research was to benefit from the post-World War Two mood in science, as many physicists who had been employed in war work turned their attention to the more benign ➲

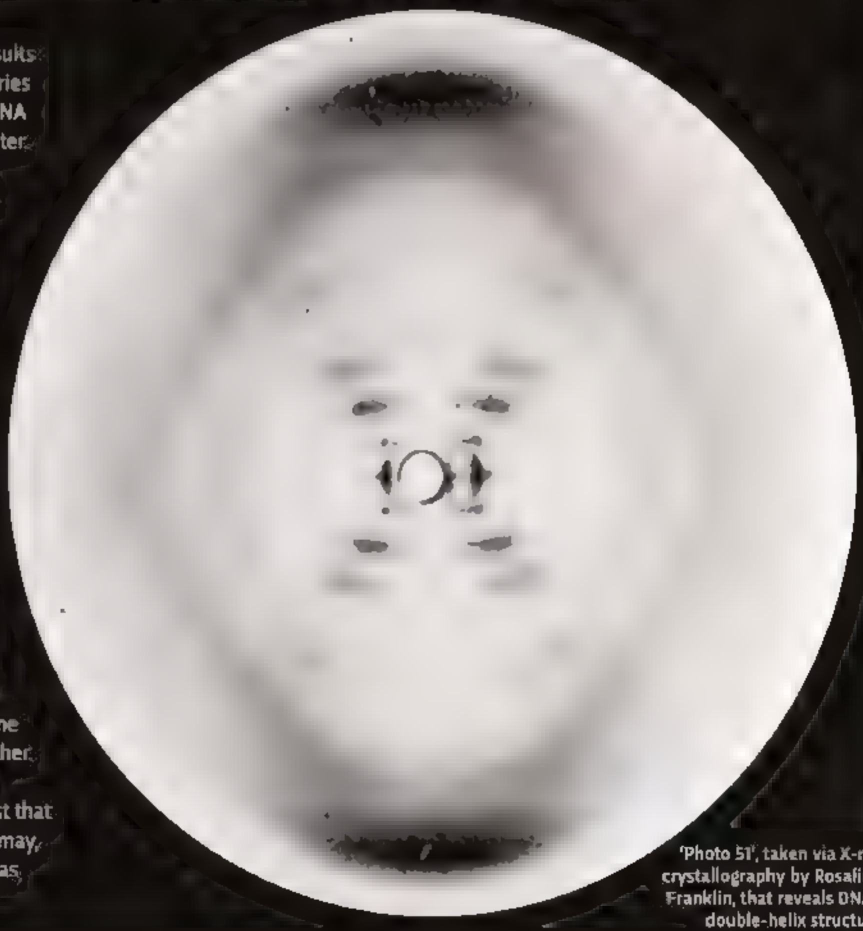
THE KEY EXPERIMENT

It was a photo taken by biophysicist and crystallographer Rosalind Franklin that held the key to determining the make-up and structure of the DNA molecule

Rosalind Franklin's key experiment – the results of which James Watson glimpsed – was a series of X-ray crystallography experiments with DNA samples containing different amounts of water. The most famous outcome of this is 1952's 'Photo 51', which revealed key details about the structure of DNA.

The more a feature is repeated within a structure, the more the film will be bombarded with X-rays diffracted in the same way, and the darker the corresponding patch in the image. The large dark patches at the top and bottom of the picture represent DNA's bases, while the X-shaped blobs indicate a helix. The arms of the cross represent the planes of symmetry in a helix viewed from the side; the 'zig' and the 'zag' of its turns. There are 10 spots on each arm of the cross before you reach the large black patch at the top, which corresponds with 10 bases stacked one on top of the other in each turn of the helix. The fourth blob from the centre is missing, which indicates that one strand of DNA is slightly offset against the other.

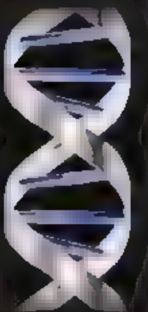
Rosalind Franklin turned her attention to Photo 51 in early 1953. Her notebooks suggest that she had gleaned all its key information and may, in time, have reached the same conclusions as Watson and Crick.



'Photo 51', taken via X-ray crystallography by Rosalind Franklin, that reveals DNA's double-helix structure

KINGS COLLEGE LONDON

TIMELINE



1869

Friedrich Miescher discovers DNA in his preparations of white blood cells extracted from the pus in surgical bandages. He calls it 'nuclein'.

1912-14

William Henry Bragg (left) and his son William Lawrence Bragg lay the foundations of X-ray crystallography when they realise they can infer the structure of crystals from the patterns of scattered X-rays.

1920s

Phoebus Levene discovers nucleotides – the combination of a sugar, base and phosphate group – and suggests they form short lengths of DNA called 'tetranucleotides'.

1937

Florence Bell arrives in William Astbury's lab and takes the first X-ray images of DNA (left). Astbury makes an attempt at a structure the following year.

1952

Rosalind Franklin takes 'Photo 51', a highly detailed image of the 'B' or hydrated form of DNA. The photo is later seen by James Watson (right) without her knowledge.

1953

Watson and Francis Crick propose a model for the structure of the DNA molecule. They publish the structure in the scientific journal *Nature* and suggest that it indicates the function of DNA.

biological problems. Among them was Maurice Wilkins, who had worked on both radar and the Manhattan Project to build an atomic bomb. By the middle of 1950, Wilkins was assistant director of King's College London's new biophysics unit. In a dank basement underneath the Thames, Wilkins and PhD student Raymond Gosling were producing much sharper X-ray pictures of DNA than Astbury had managed.

Rosalind Franklin was invited to join the unit's DNA research in 1951, bringing with her important crystallography skills after making her name in Paris with X-ray insights into the structures of coal, carbon and graphite. But misunderstandings with Wilkins over her role in the DNA research caused a rift that arguably cost them the scientific race.

One of the biggest discoveries Franklin made in her time at King's was to discover, along with Gosling, that there are two forms of DNA: a dehydrated, tightly packed 'A' form and a hydrated, longer 'B' form, which produced different X-ray patterns. Astbury's blurry images must have been a combination of the two.

The King's group, and Franklin in particular, believed that the structure would emerge from careful X-ray work. But at the Cavendish Laboratory in Cambridge, now headed by William Lawrence Bragg, a pair of researchers called James Watson and Francis Crick had other ideas.

The race heats up

Watson, an American researcher in his 20s, and Crick, older with a reputation for a sharp mind, did famously little in terms of experiments with DNA. Instead, they chose to build physical models to work out how DNA's known components could fit together. Much of their experimental knowledge came from seminars and informal chats with Wilkins, with whom they were on friendly terms.

At the end of 1951, Watson and Crick invited the King's team to see their latest model, which they believed to be the structure. Informed by Watson's memory of a talk by Franklin, it was made up of three DNA chains with the sugar-phosphate backbone on the inside and the bases on the outside. Franklin immediately knew it was wrong – DNA's water content meant the backbone had to be on the outside. Embarrassed, Bragg banned the pair from any more DNA work.

In May 1952, Franklin took Photo 51 – a stunningly clear picture of the B form of DNA (see 'The Key Experiment', page 59). Abiding by an earlier agreement with Wilkins to focus on the A form, she put it aside. By January 1953, Franklin had decided to leave King's for Birkbeck College and began sharing her work with Wilkins. Wilkins, who had long believed that DNA was a helix, showed the image to Watson, who later wrote: "The instant I saw the picture, my mouth fell open and my pulse began to race." Photo 51 immediately spelt out 'helix' to Watson, who returned to Cambridge suitably inspired.

In February 1953, Linus Pauling, a giant of molecular biology and an expert in protein structure, proposed his own structure. But with only Astbury's earlier data to go on, he got it wrong. Among other basic mistakes, he suggested that DNA was comprised of three chains.

Watson and Crick, concerned that Britain would lose the race and seeing a chance for themselves, returned to their model-building. They knew how far apart the bases were, that DNA's backbone was on the outside of the molecule, that the overall structure was a helix and that it was probably made of two chains. They also saw more of Franklin's data, this time via a report to the biophysics committee of the Medical Research Council, which funded both groups. From this, Crick was able to deduce that the chains in the DNA molecule look the same upside-down and must therefore run in opposite directions.

The final piece of the puzzle was a 1949 experiment by the biochemist Erwin Chargaff. He determined that the number of As matched the number of Ts, and the number of Cs matched the Gs. Watson and Crick realised that As must always bond to Ts, and

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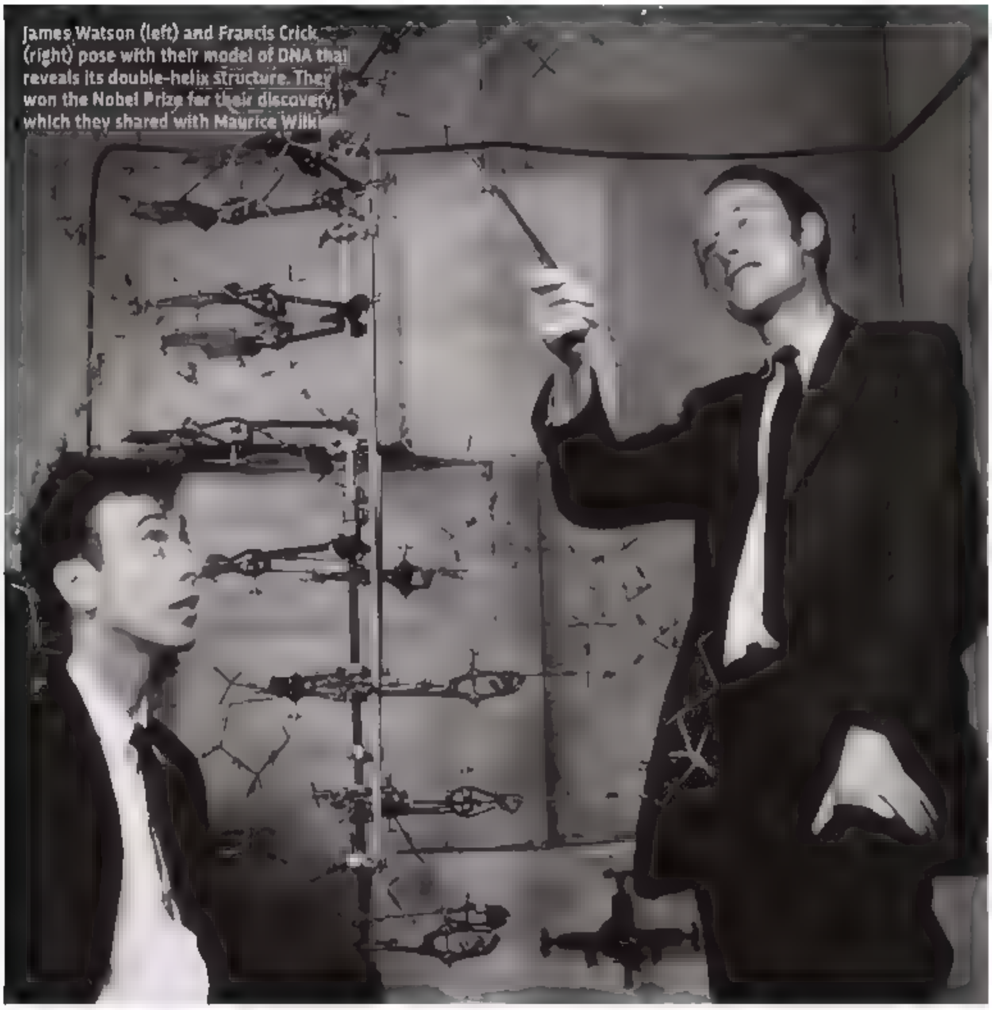
> “The instant I saw the picture, my mouth fell open and my pulse began to race”



James Watson (left) and Francis Crick (right) pose with their model of DNA that reveals its double-helix structure. They won the Nobel Prize for their discovery, which they shared with Maurice Wilki[illegible]

Cs to Gs, producing a ladder-like helix with the paired bases forming the rungs and the sugar-phosphate backbones the sides.

Model completed, the pair went for lunch in a nearby pub called The Eagle and declared that they had found the meaning of life. When the King's team visited this time, they accepted the model immediately. “Rosy's instant acceptance of our model at first amazed me,” Watson wrote later. “Nonetheless… she accepted the fact that the structure was too pretty not to be true.”

Crick and Watson's structure was published in the journal *Nature* in April 1953, along with two articles from King's. None revealed the role that the King's data had played and Franklin died in 1958, perhaps never having known. Watson, Crick and Wilkins went on to share the Nobel Prize in 1962.

Watson and Crick wrote in their 1953 paper: “It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material.”

In the years since 1953, researchers have learned how DNA copies itself and how its strings of As, Ts, Cs and Gs provides a template for making proteins. More recently, analysis of the human genome has allowed scientists to glimpse the intricacies of how DNA orchestrates life **SF**

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by **KATHERINE NIGHTINGALE**
@katnightingale| Katherine is a science writer with a masters in molecular biology

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NEED TO KNOW

Get to grips with the [illegible]ructure of DNA with these key terms

DOUBLE HELIX

[illegible] [illegible]ses form the steps and the [illegible]sphate backbone [illegible]

NUCLEOTIDE

[illegible]nit of DNA. Ea[illegible] [illegible]eotide is made up of a base [illegible] [illegible]etters' of DNA: adenine [illegible]uanine (G), thymine (T) or [illegible] [illegible]oup. T[illegible] [illegible]ucleotides form th[illegible] [illegible] complementary chain[illegible] [illegible] with adenine matched [illegible]ymine and guanine [illegible]

PHOSPHATE GROUP

[illegible] phosphorous atom [illegible]urrounded by oxygen a[illegible] Phosphate groups, along with [illegible]eoxyribose sugars, make up [illegible]he 'backbone' of the lon[illegible] DNA molecule

X-RAY CRYSTALLOGRAPHY

This is the study of the [illegible]tructure of crystals by firing [illegible] [illegible]ounce off th[illegible] [illegible]

THE COMPOSITION OF HUMAN CELLS

The invention of the microscope kick-started a scientific journey of discovery that culminated in our understanding of the building blocks of the human body. *Katherine Nightingale* tells the story

When people think of scientists, they often think of people in white coats peering down microscopes. That's no surprise – the microscope has been instrumental to finding out what's inside us. The first microscope came from the Dutch city of Middelburg around 1590. This was a time of great interest in the power of lenses, whether for spectacles, magnifying glasses, telescopes or microscopes. Some would use these new technologies to gaze into the heavens. Others peered inwards, instead staring into the 'microcosmos', the world of cells inside us.

During the 1600s, scientists began to study all kinds of materials under their microscopes. Not least of these was Robert Hooke, who in 1661 was passed a royal commission to study insects. Hooke set about designing a new type of microscope for the job. With its three lenses, it magnified objects by 50 times.

He studied insects and materials, producing brilliant technical drawings for his *Micrographia* book, published in 1665. *Micrographia* also holds Hooke's most significant contribution to cell biology. When peering down his microscope at a thin sheet of cork, he saw what appeared to be many empty spaces bound by wall-like structures. Reminded of the small rooms in which monks dwell, he named them 'cells'.

Perhaps drawn to microscopy after seeing Hooke's studies of fabrics, Dutch tradesman Antonie van Leeuwenhoek became adept at grinding lenses that he could magnify objects to 270 times their size. His microscopes used just a single, tiny spherical lens, and gave him unprecedented access to the hidden microscopic world.

A louse clinging to a human hair is one of the remarkable images that features in Robert Hooke's *Micrographia*

In 1675 he found single-celled lifeforms – now called protozoans – in drops of rainwater and in 1683 he studied his own tooth scrapings and found bacteria, tiny moving beasts he named animalcules ('little animals').

Cells are generally transparent, making it difficult to discern their contents, even with improved microscopes. Van Leeuwenhoek is the first thought to have used cell 'stains', adding saffron to muscle cells to increase the contrast between cell components. Together Hooke and van Leeuwenhoek are credited with discovering cells, a feat that would have been impossible without their microscopes.

The life within

Humanity had found cells, but what were they? It was the discovery of their first component that would bring about a deeper understanding of their role, and what Hooke's dead cork cells had in common with van Leeuwenhoek's little animals.

Even though many others must have spotted it, it was the Scottish botanist Robert Brown who first named and described the cell nucleus – the control centre – in orchid cells in

This artist's impression of a human cell shows organelles surrounded by cytoplasm and a membrane

IN A NUTSHELL

Harnessing the power of microscopes enabled scientists to explore a world invisible to the naked eye and discover that plants and animals are comprised of cells. Technological advances then meant we could learn how cells work

CAST OF CHARACTERS

The great minds who harnessed cutting-edge technology of the time to explore life

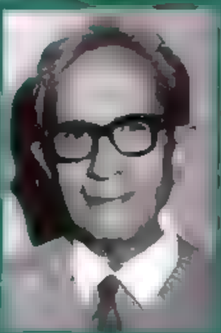
ROBERT HOOKE (1635-1703) contributed to fields as diverse as architecture, palaeontology and astronomy. He was an English researcher, born on the Isle of Wight and known for his difficult manner and rivalry with fellow researcher Isaac Newton.

ANTONIE VAN LEEUWENHOEK (1632-1723) was a Dutch draper and [illegible] led to him producing some of the most advanced microscopes of his time, and the discovery of [illegible] celled [illegible]

THEODOR SCHWANN (1810-1882) was a German physicist born in the town of Neuss. He was most productive early in his career, making discoveries in digestion, the nervous system and metabolism, before turning his attention to theology later in life.

CAMILLO GOLGI (1843-1926) was an Italian [illegible] and [illegible] concentrated his work on the nervous system, though he also strayed into malaria research. Many of his discoveries are named after him, as is the [illegible]

ALBERT CLAUDE (1899-1983) moved to [illegible] a Belgian cell biologist who served for the British intelligence Service during World War One, and was rewarded with a medical education in Belgium despite not having the required qualifications.



1831. We now know that the nucleus contains the chromosomes of DNA and is the seat of power from which our genes regulate the rest of the cell.

A few years after Brown named the nucleus, in 1837, the German scientist Theodor Schwann was having lunch with a fellow German researcher, the botanist Matthias Schleiden. Their conversation turned to the nucleus, which had so far been seen only in plants. Schleiden had observed that new plant cells seemed to come somehow from an existing nucleus. Schwann, who had been studying animal cells, remembered seeing structures that could well be nuclei.

Excited, the pair rushed to Schwann's laboratory to look at tadpole tissue. There were the nuclei: animals must be made of cells too. Both scientists wrote up their findings, with Schleiden describing cells as the 'building blocks of life', and Schwann stating: "All living things are composed of cells and cell products." It may seem obvious now, but this 'cell theory' was revolutionary: all life from algae to aardvarks, bacteria to begonias, was made of cells.

Wealth of discoveries

The subsequent decades of the 19th century, as microscopes improved, were fertile times for discovering the components of cells and teasing apart the differences between the cells of animals, plants and bacteria.

Hooke, when coining the term cells, had technically discovered the cell wall in 1665. Human cells don't have a cell wall like plants and some bacteria, but they do have a cell membrane, a layer of lipids (fatty molecules), proteins and other components. Though it was clear that something must surround animal cells, it wasn't until 1855 that the doctor Robert Remak found a way of hardening the membrane so he could see it clearly.

About 70 per cent of the volume of the cell is cytosol, a colourless liquid that is mostly water, plus salts and organic molecules. Together with components called organelles, cytosol makes up the cell's cytoplasm –

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> "The mitochondrion is the cell's 'powerhouse' because it produces a molecule that is used as a source of chemical energy"

everything in the cell membrane aside from the nucleus. Around 1835, the French biologist Félix Dujardin saw this 'life substance' in single-celled animals and named it sarcode (meaning 'the flesh of the cell').

In the mid-19th century, life was made a little easier for the nascent field of cell biology. Until this point a variety of natural dyes such as iodine, cochineal and van Leeuwenhoek's saffron had been used to stain cells. But in 1856, a young assistant chemist named William Perkin produced mauve, the first synthetic dye. Though not designed for cells, it was the first of many useful synthetic dyes.

Internal organelles

Many cellular metabolic processes take place in the cytosol, but some occur in dedicated organelles. One of the best-known organelles is the mitochondrion, now known as the cell's 'powerhouse' because it produces a molecule that is used as a source of chemical energy. It's possible that mitochondria were first seen in muscle cells by the Swiss physiologist Albert von Kolliker in 1857. But it was Richard Altmann, in 1894, who established that they were organelles and called them 'bioblasts'. They ➲

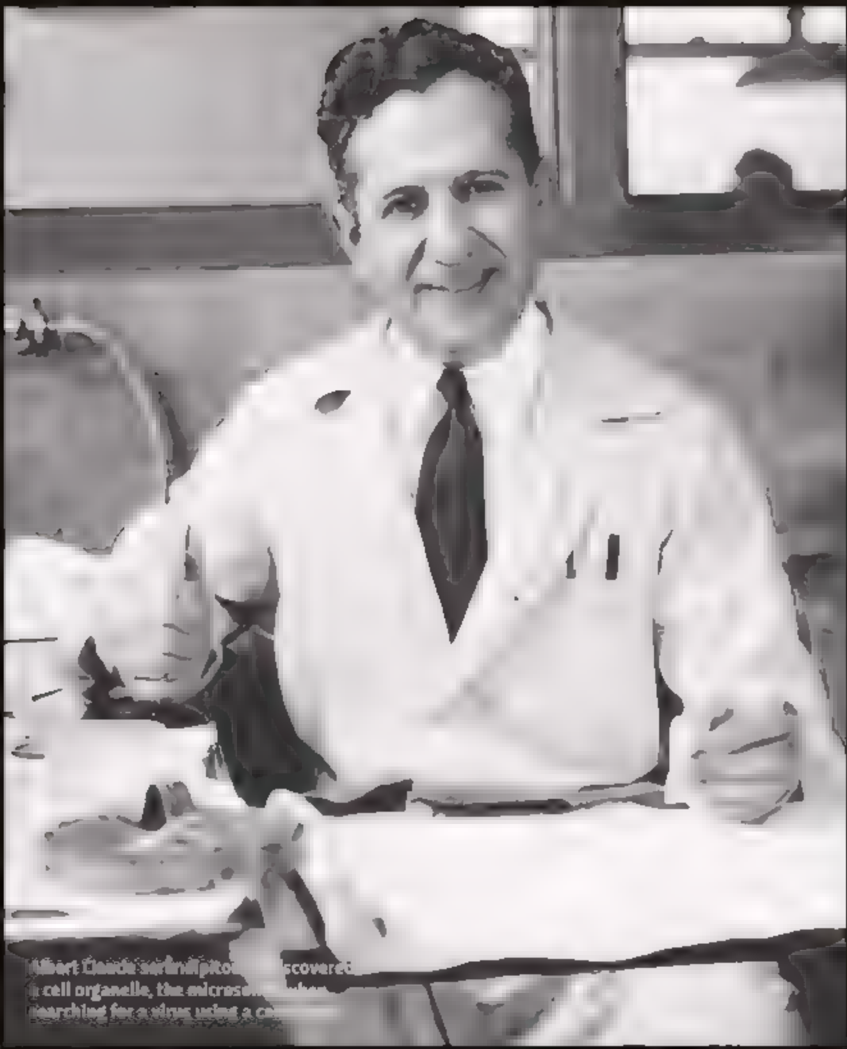
THE KEY EXPERIMENT

Sometimes major scientific discoveries happen by chance, as Albert Claude found when he stumbled upon a key organelle while searching for a virus in the cells of a chicken

Much was known about the cell by the time that Albert Claude performed his key experiment of developing cell fractionation in 1930. But looking down a microscope was quite different to being able to separate out the parts of the cell to study them individually.

Claude developed cell fractionation while trying to isolate a virus, called Rous Sarcoma Virus, from chicken tumours. To do this he gently mashed up the tumour cells with a pestle and mortar (or sometimes a commercial meat grinder) to break the membranes and release the cell contents. He then put them in a tube and spun them in a centrifuge, the force of which speeds up the settling of heavier particles to the bottom of the tube. By successively spinning and extracting the sediment, the components of the cells are separated by size.

Claude found what he was looking for – a virus made of Ribonucleic acid (RNA). Good scientists run 'control' experiments too. In this case, Claude needed to show that the virus was present in only the tumour cells, and not healthy chicken cells. But when he repeated the process, he found that healthy cells also had similar RNA-rich particles in them. He named these mysterious organelles 'microsomes', discovering for the first time an organelle that researchers using a light microscope simply would not have spotted.

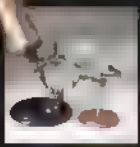


Albert Claude serendipito[illegible] discovered a cell organelle, the microso[illegible] when searching for a virus using a c[illegible]

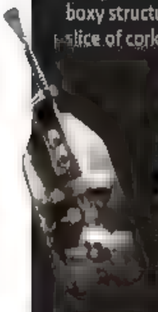
ROCKEFELLER ARCHIVE CENTER

TIMELINE

1665



Robert Hooke's *Micrographia* is published, in which he describes using a microscope to find boxy structures in a thin slice of cork and coins the term 'cell'.

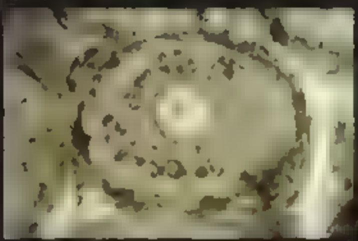


1675

Antonie van Leeuwenhoek uses his powerful microscope (left) to discover 'little animals' – single-celled organisms – in rainwater, followed by bacteria from his own tooth scrapings in 1683.

1837

Matthias Schleiden and Theodor Schwann discuss the recent discovery of the nucleus and realise that both plants and animals must be made up of the same basic units – cells.



1897

Camillo Golgi discovers the Golgi apparatus in nerve cells using the 'black reaction', his own staining technique, which involves impregnating cells with silver nitrate (above).

1939

Albert Claude develops the technique of cell fractionation in an attempt to isolate a chicken virus. He discovers ribosomes and isolates mitochondria in the process.

1945

Albert Claude and colleagues produce the first electron microscope image of a cell (above), which George Palade describes as cell biology's "birth certificate".

were renamed mitochondria by the German cell biologist Carl Benda in 1898

Another organelle was discovered as a direct result of cell staining, and is also the only one to bear the name of its discoverer. In 1897, Camillo Golgi discovered an organelle called the Golgi apparatus in a makeshift lab he had set up in a small hospital kitchen. It was there that he developed the 'black reaction' in which cells are impregnated with silver nitrate, highlighting their contents under the microscope. The Golgi appeared as a fine network inside the cell, and we now know that it is involved in the packaging up of proteins and lipids made by the cell

As the 20th century dawned, most of the large components of the cell had been spotted and named. Getting to grips with what each part of the cell did was going to take more than looking, however. As the Belgian cell biologist Albert Claude said in his 1974 Nobel lecture: "Until 1930 or thereabout, biologists, in the situation of astronomers, were permitted to see the objects of their interest, but not to touch them; the cell was as distant from us as the stars and galaxies."

Peering deeper

At the same time, the tool that had been their window into cells – the light microscope – was coming to the end of its usefulness, unable to resolve objects smaller than the wavelength of light

Two techniques developed in the first half of the 20th century would come to the rescue, revealing structures invisible to the light microscope, confirming previous findings, and working out the biochemical role of organelles.

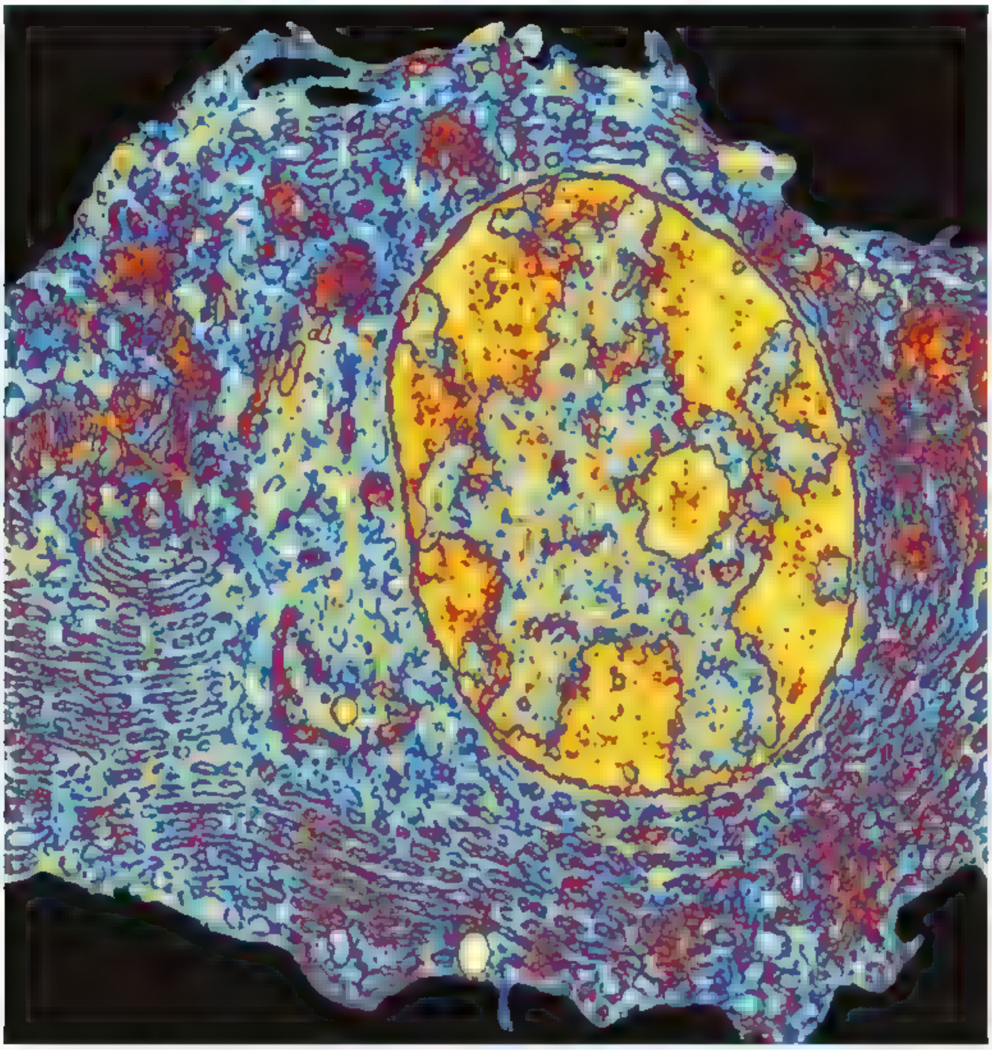
The first of these, cell fractionation, allowed scientists to get their hands on cellular components. Developed in 1930 by Albert Claude at the Rockefeller Institute in the US, it involved mashing up cells and then using the process of centrifugation to separate their subunits (see 'The Key Experiment', page 65). The second essential technique was electron microscopy, invented by German engineers in 1931. Physicists were already using the technology, but it was Claude who brought it into the realm of biology.

Electron microscopy uses a beam of electrons as a source of illumination and can resolve much smaller objects than traditional microscopes because the wavelength of an electron is much shorter than that of a photon (a packet of light). In 1943, Claude began working with one of the few electron microscopes in the US to look at subcellular particles produced by cell fractionation. In 1945, his lab was the first to use an electron microscope to image a whole cell. Claude shared the Nobel Prize in 1974 with Christian de Duve, a Belgian researcher, and George Palade, who later called Claude's image the "birth certificate" of cell biology.

Claude's lab was able to combine these techniques to determine what mitochondria do; they may have been observed and named in 1894, but it was only once they had been isolated that researchers could find out their function. He found that they contained many enzymes (proteins that act as catalysts) associated with the chemical process of respiration, and that they are indeed the cellular power plants. He also used characteristic dyes to conclude that the organelles in his test tube were the same that had been seen under the microscope.

Also in 1945 Claude, along with colleague Keith Porter, used electron microscopy to discover the endoplasmic reticulum (ER), a large membranous system within the cell that is involved in producing proteins and lipids, and transporting them around the cell. The net-like structure had initially been spotted in 1902 by the Italian scientist Emilio Veratti, but the idea was discarded by the scientific community at the time.

In 1946, George Palade joined Claude's lab and began to refine many of his techniques. It was Palade who realised that the microsomes that Claude had discovered in his key experiment can be part of the ER.



A cross-section of a human cell taken with an electron microscope reveals the nucleus (large oval centre) surrounded by cytoplasm. This is filled with the endoplasmic reticulum – seen as a red/orange network

He renamed them ribosomes in 1955 and found that they produce proteins. We now know that the membrane of the ER joins the outer membrane of the nucleus, providing a highway along which DNA is translated into proteins. Part of it, the 'rough' ER, has ribosomes attached, and another, the 'smooth' ER, produces lipids.

Waste disposal

Christian de Duve took these new techniques further by discovering an organelle without using a microscope – he didn't even have one in his lab at the time. In 1949, de Duve discovered lysosomes – the waste disposal unit of the cell – by accident when researching insulin in rat liver cells. He used cell fractionation and then biochemical tests to determine that the cell's cytoplasm contains numerous lysosomes – membranous particles of enzymes playing a role in cell communication and energy metabolism, as well as breaking down cellular components.

Researchers have discovered much more about the cell since then. But it's fair to say that today's cell biologists are more preoccupied with how the components work together than finding new ones. They tease apart the relationships between these cellular subunits – how they talk to each other to keep the delicate equilibrium of the cell's workings in check; how they behave in certain circumstances, and how this knowledge can be exploited to develop drugs and other treatments.

It is now possible to watch living cells go about their business, using the modern versions of van Leeuwenhoek's saffron to watch specific parts of the cell in action. Today's image of the cell is dynamic – a high-definition film to the 17th century's hand-drawn sketch **SF**

by KATHERINE NIGHTINGALE
@kathnightingale Katherine is a science writer with a masters in molecular biology

NEED TO KNOW

[illegible] you understand the workings of cells

CELL

[illegible]e basic unit of li[illegible] [illegible]thing is made up of cel[illegible] Human cells have geneti[illegible] [illegible]erial containing a nucle[illegible] and membrane-enclosed [illegible] all in a watery [illegible]ostance called the cytoso[illegible] [illegible]rrounded by a[illegible] [illegible]embran[illegible]

EUKARYOTIC

[illegible]type of cell that has a nucleus and membrane-enclosed organelles. Plant, animal and [illegible] cells are eukaryotic [illegible]e single-celled [illegible]

ORGANELLE

[illegible]mponent of the cell tha[illegible] [illegible] organ [illegible] [illegible]e body [illegible] [illegible]eparated from th[illegible] own membra[illegible]

PROKARYOTIC

[illegible] [illegible]hondria or othe[illegible] [illegible] [illegible]s bacteria

THE THEORY OF EVOLUTION

Charles Darwin put the pieces together, but he wasn't the only radical thinker when it came to evolution. *Professor Rebecca Stott* reveals how other naturalists Alfred Russel Wallace and Jean-Baptiste Lamarck were also pioneers

Most people know that the theory of evolution did not appear like a bolt from the blue with the publication of Charles Darwin's *On the Origin of Species* in 1859. But not many people are aware that the idea has been around in various forms for at least 2,500 years.

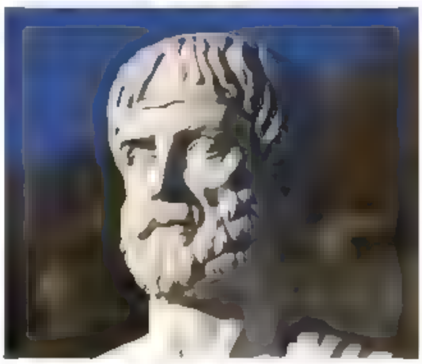
Like us, the ancient Greeks failed to agree about the origins of life. Their cosmologies were profoundly different from our own. There were no heresy laws or inquisitions to fear or a dominant creation story to side-step. Ancient Greek cosmologies were wildly variant: some believed that life had been shaped by gods; others that it had come into being through atoms colliding chaotically.

Empedocles – poet, healer, magician and 'controller of storms', as well as a philosopher – produced a surreal foreshadowing of natural selection 2,500 years ago on the island that we now call Sicily. He proposed that life had started out as random body parts – eyes, necks, arms, teeth and so on – suspended in a primeval soup. Collisions had produced random combinations – men with the heads of cattle; animals with branches for limbs. Some of these combinations had proved viable, others not.

A century later, Aristotle declared Empedocles's theory absurd and unverifiable. Having studied under Plato in Athens, he spent two intense years examining animals and plants on the island of Lesbos in the Aegean Sea in an attempt to discover the laws of nature through close observation rather than by guesswork. Nature was not random and chaotic, he declared, it was eternal and deeply, perfectly patterned. Each organism fitted its place. The flesh of an individual plant or person might bloom and decay, but species remained unchanging.

Aristotle was no evolutionist, but his emphasis on close observation above speculation makes him integral to this long history of evolution. He is considered the father of biology.

No work rivalled that of Aristotle's detailed study of species for nearly a thousand years. In 9th-century Baghdad, Al-Jahiz, an Arab philosopher working at the heart of the Abbasid Empire, having been inspired by Aristotle's recently translated volumes, set out to write his own compendium of zoological knowledge. In his seven-volume work *Living Beings*, he described the natural world in terms similar to the modern concept of ecosystems; he also saw everywhere what we would call the adaptation and diversification of species.



Aristotle realised that the natural world was actually ordered, rather than being chaotic and random

Some scholars claim that Al-Jahiz discovered natural selection a thousand years before Darwin: they see natural selection in his descriptions of systems of predation, co-dependency and survival, but Al-Jahiz was a devout Muslim and his volumes, as an act of worship of Allah, described a natural world in which everything had been assigned its place in a divinely ordained system. It was not a mutable system.

In 15th-century Milan, the painter, inventor and polymath Leonardo da Vinci read Arabic and Greek philosophy and natural sciences. One of the natural philosophical questions that vexed him was how fossilised oyster beds had got themselves into the tops of mountains. But though he asked questions that would lead 19th-century geologists to evolutionary

STOCK GETTY

IN A NUTSHELL

Many theories have a long history, but few are as rich as evolution. Even the ancient Greeks touched on evolution before the great thinkers of the 18th and 19th centuries bore it out with a remarkable idea: natural selection.

Finches that Darwin used as evidence for a theory of evolution rest on his masterwork *On the Origin of Species*

"Da Vinci took risks asking heretical questions. He may have developed his mirror-writing technique to protect the ideas in his notebooks from prying eyes"

conclusions, he was not that interested in questions of species.

What da Vinci saw in fossils was evidence to support his neo-Platonist beliefs: that the human body was a microcosm of the Earth and was subject to similar laws. Da Vinci was taking significant risks in asking such heretical questions about the nature of the Earth. Indeed, he may have developed his mirror-writing technique to protect the ideas in his notebooks from the prying eyes of inquisitors and priests.

Through the 18th century, the publication of new works on insects and the development of microscopes inspired a generation of young men to study the reproductive behaviour of microscopic organisms. Occasionally they discovered disturbing and inexplicable things.

In the summer of 1740, Abraham Trembley, a young Swiss tutor educating the sons of the Count of Bentinck in The Hague, sent his young charges to collect pond water for the microscope. He proposed that they do some experiments on the creatures (he called them polyps; we know them as Hydra) they found in the estate's ornamental ponds. Trembley was astonished to discover that, when he cut the organisms in half, they regenerated themselves. Such a phenomenon appeared to violate the prevailing understanding of natural laws: plants re-grow after cutting; animals don't. But the polyp did.

The polyp quickly became the talk of European salons and were used by materialists and atheists alike to

THE KEY EXPERIMENT

Natural selection was the most important milestone in the long history of evolution, because it provided a mechanism to explain how the theory worked

The crucial breakthrough in the history of evolution is a 'convergent' one. In 1858, while suffering from malaria on the Malay Archipelago, Alfred Russel Wallace came up with the idea of natural selection: the process by which some species survive and others die out, encapsulated in the phrase 'survival of the fittest'.

Charles Darwin had already found evidence for natural selection during his travels around South America aboard the Beagle during the 1830s. Darwin understood that evolution worked through a struggle for existence in which favourable variations would tend to be preserved and unfavourable ones destroyed. The result of this would be the formation of new species. From this point on, Darwin committed himself to gathering more evidence. This is one of the reasons why it took him so long to publish his landmark book *On the Origin of the Species*.

When Wallace sent him his still-unpublished essay on natural selection in 1858, Darwin finished his book in a matter of weeks and rushed it to press. The Linnaean Society declared Darwin the first to have discovered natural selection because he was able to submit evidence that he had defined the idea – though not published it – many years before Wallace

An illustration from *The Malay Archipelago* by Alfred Russel Wallace (1874). The work described Wallace's thoughts that led to the idea of natural selection and a theory of evolution

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demonstrate that life was to be found within material flesh not outside it. Debates about the nature and origins of life had taken a strange new turn.

Altogether stranger evolutionary ideas began to emerge in Cairo around the turn of the 18th century. The French consul here, Benoît de Maillet, had brought the philosophical questions of the French salon culture – debates about the age, origin and nature of life on Earth – to Egypt. The ancient remains he saw in the desert suggested that the Earth was much older than the French Catholic priests claimed. The Arab traders and religious leaders who Maillet met proposed quite different cosmologies and ways of understanding the Earth's formation. He became convinced that Egypt – indeed, the Earth's crust as a whole – had been formed by waters gradually receding from a universal ocean and that all humans had evolved from 'seapeople'. Some of these intermediate forms, he proposed, still survived. He spent his fortune travelling around Europe collecting evidence of seamen sightings. Due to the heretical nature of his claims, he was unable to publish his strange book, *Telliamed* (his own name spelt backwards) during his lifetime. It only began to circulate, clandestinely, half a century later.

Freedom of thought

By the 18th century, Paris and Amsterdam had become hubs of intellectual subversion, part of a network that stretched across Europe; anti-clerical books, pornography, atheism and books on natural science or free thought travelled down the same routes. In Paris, the newly formed secret police were determined to keep unorthodox philosophers under surveillance.

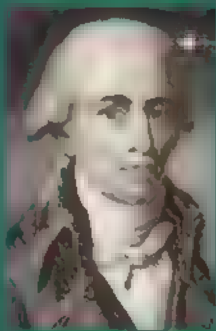
The playwright, philosopher and encyclopaedist Denis Diderot was one of the most dangerous subversives according to the police files. Diderot had read papers about Trembley's polyps, Maillet's *Telliamed*, and most new papers and books on the natural sciences. In his plays, philosophical speculations and encyclopaedias, ➲

SCIENCE & SOCIETY X2 GETTY SCIENCE PHOTO LIBRARY ALAMY

CAST OF CHARACTERS

[illegible] 18th and 1[illegible] [illegible] the ide[illegible]

ERASMUS DARWIN (1731-1802) was a Derbyshire inventor, poet and d[illegible] who proposed in *[illegible]onomia* [illegible] that all living beings had evolved from simple aquatic organisms. He was the grandfather of Charles Darwin



JEAN-BAPTISTE LAMARCK (1744-1829) A French professor of invertebrates. He proposed that all [illegible] had evolved through great lengths of time from simple to complex organisms through the inheritance of acquired characteristics

ROBERT CHAMBERS (1802-1871) was a Scottish publisher and encyclopaedist, who published *Vestiges of the Natural History of Creation* in 1844. It was an attempt to marry together all the recent discoveries in the sciences to [illegible] that the Earth [illegible] on it had transmuted from simple organisms

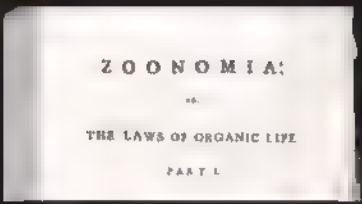
CHARLES DARWIN (1809-1882). The British naturalist published *On the Origin of Species by Natural Selection* in 1859. It proposed that natural selection – the survival of the fittest – was the mechanism by which evolution worked

ALFRED RUSSEL WALLACE (1823-1913) was a British collector and naturalist who in [illegible] discovered natural selection while out in the Malay Archipelago

TIMELINE

1748

The *Telliamed*, written by Benoît de Maillet (right) between 1722 and 1732, is published posthumously. Maillet proposes that humans have evolved from aquatic organisms and that intermediate half-animal half-fish creatures survive.



ZOONOMIA;

OR,

THE LAWS OF ORGANIC LIFE.

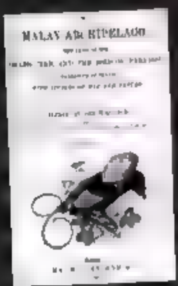
PART I.

1794-6

Erasmus Darwin publishes *Zoonomia*, or the *Laws of Organic Life*, a two-volume medical treatise containing a chapter called 'Generation' in which he proposes that all living beings have evolved from aquatic filaments.

1802

A Professor of Invertebrates in Paris, Jean-Baptiste Lamarck (right), gives a lecture in which he proposes that all species have evolved through great lengths of time and that they have evolved through the need to adapt to the environment.

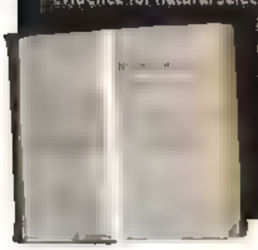


1858

While in a delirious fever caused by malaria on the Malay Archipelago, Alfred Russel Wallace comes up with the idea of natural selection.

1859

Charles Darwin publishes *On the Origin of Species* in which he provides detailed evidence for natural selection, as well as a carefully extended argument for this being the mechanism by which evolution works.



he proposed that the Earth was inconceivably old, that species had mutated through time and that man would one day become extinct.

Like Maillet and his contemporary the Comte de Buffon – who slipped evolutionary ideas into his great volumes on the history of the animals – Diderot, fearful of prison, published his most radical ideas posthumously.

A few decades later, the French Revolution produced the conditions in which evolutionary ideas flourished most rapidly. There were no priests to police philosophical questions or threaten inquisition. Napoleon had brought the largest collection of natural history specimens in history into the Museum of Natural History in Paris, specimens looted from European palaces. He appointed 12 professors to the Jardin des Plantes to work on a number of natural philosophical problems, alongside students from all over Europe. It was not long before the most carefully worked-out theory of evolution thus far emerged.

From 1801 until his death in 1829, the Parisian Professor of Invertebrates and Worms, Jean-Baptiste Lamarck, proposed that nature had worked to transform species over unimaginable tracts of time from single-celled to complex organisms. The environment caused animals to adopt new habits to survive, he claimed; in so doing they produced new structures – teeth, limbs, long necks. His ideas were both mocked and refuted by his more powerful and influential colleague in the Jardin, the great comparative anatomist Georges Cuvier.

Thinking alike

Lamarck and Erasmus Darwin reached similar conclusions about the evolution of species at about the same time, without knowing each other and by different routes. Darwin, who was a poet and inventor as well as a doctor, proposed that all organisms had once been aquatic filaments in a universal ocean. Such ideas were dangerous; in the wake of the revolution, Darwin and his philosopher friends were also under surveillance. Like Diderot, Darwin slipped his most controversial ideas into footnotes or into his poetry; his most radical theories were published posthumously.

In the first decades of the 19th-century, Lamarck's influence fanned out from Paris across Europe; the thousands of young and idealistic students who studied with him took Lamarckian ideas like seeds back across the world. Many used them to underpin reformist agendas.

In 1825, a 16-year-old Charles Darwin arrived in Edinburgh to study at medical school and was befriended by a physician who had studied with Lamarck. Robert Grant, explained Lamarck's ideas to the young Darwin and reminded him of how remarkable his grandfather Erasmus's ideas had been. When he set off on the Beagle reading Charles Lyell's *Principles of Geology*, he opened a notebook that he titled the *Transmutation Notebook*. His hunt for proof of the mutation of species had begun.

The branching and converging patterns in this history continue. In Scotland in the late 1830s, as Darwin returned from the Beagle voyage with an embryonic theory of natural selection, a young publisher called Robert Chambers found himself converted to transmutationism by reading accounts of Lamarck and Erasmus Darwin's ideas. His sensational book *Vestiges of the Natural History of Creation*, published anonymously in 1844, was elegantly written and cheap to buy. It fused together new discoveries in zoology, botany and geology to give an account of Earth's history and of the evolution of species. *Vestiges* made a number of mistakes in its accounts of new scientific discoveries and shocked the establishment to its core. But, by bringing evolution into the drawing rooms of the public, it paved the way for new, more evidence-based theories.

A remarkable young land surveyor called Alfred Russel Wallace read *Vestiges* in the Leicester public library in the late 1840s. A few weeks later, he read Thomas Robert Malthus's Essay *On the Principle of Population*. *Vestiges*, Wallace told friends, was the

SCIENCE PHOTO LIBRARY, GETTY, ALAMY X3

Napoleon's specimen collection at the Museum of Natural History in Paris sparked a surge of interest in theories of how life on Earth was able to become so diverse

book he'd been waiting for all his life: a coherent account of the history of the Earth. But Wallace was also frustrated at the lack of proof *Vestiges* provided. When he set off with his friend Edward Bates to collect natural history specimens in Brazil, he determined to bring back the evidence.

Ten years later, an exhausted Wallace, hallucinating his way through a malaria attack on an island in the Malay Archipelago, suddenly saw how evolution might work: "It occurred to me to ask the question, Why do some die and some live?" he wrote. "And the answer was clear, that on the whole the best fitted survive…"

Back in Britain, Charles Darwin already knew this. He'd begun to put his theory of natural selection together in his notebooks of the 1830s and, by 1844, had developed these ideas into an unpublished essay. But that essay was still locked away in a drawer. Busy working on the Beagle collection, distracted by an eight-year project on barnacles, and alarmed at the amount of vitriol *Vestiges* had drawn from the establishment, he'd determined to bide his time.

When Wallace wrote to him in 1858 and sent him his essay on natural selection, Darwin was devastated. He brought in his friends to adjudicate: he needed to know the gentlemanly way to behave. The Linnaean Society gathered and made their judgement: Darwin had drafted the idea 10 years before Wallace. Wallace gracefully conceded. He explained that he'd never claimed priority and instead was honoured to be associated with the idea and with the distinguished Charles Darwin.

Historians still debate the ethics of that decision, but as a consequence Wallace returned to his beloved fieldwork while Darwin began the long and difficult campaign to defend the theory. Darwin, with his collection of detailed evidence, his persuasive rhetorical skills, reputation, status and wide circle of supporters, was without doubt the better man for that task. **SF**

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by **PROF REBECCA STOTT**

(@RebeccaStott64) *Prof Stott is the author of Darwin's Ghosts: in search of the first evolutionists*

ALAMY

NEED TO KNOW

Important terms surrounding the [illegible] of evolution

LAMARCKISM OR LAMARCKIAN EVOLUTION

[illegible] nown as soft inheritanc[illegible] [illegible] an organism [illegible] ter the [illegible] is named afte[illegible] the French biolog[illegible] [illegible]-Baptiste Lamarc[illegible]

NATURAL SELECTION

[illegible] erited traits o[illegible] [illegible]

TRANSMUTATION

[illegible] in alchemical theory

THE FUNDAMENTALS OF LIFE

THE HISTORY OF BRAIN RESEARCH

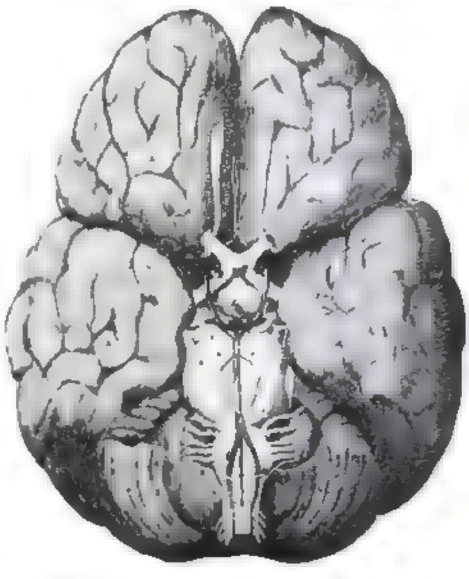
Doctors and neuroscientists have been attempting to unravel the secrets of the brain for centuries – but it has proved a tough nut to crack. *Dr Christian Jarrett* charts the major discoveries

Rome, 2nd century AD. An audience of philosophers and politicians has gathered to watch Galen of Pergamon, the 'prince of physicians', perform a public demonstration involving a pig. The animal's squealing falls suddenly silent as Galen severs its laryngeal nerve – the neural link connecting its voice box to its brain. The crowd audibly gasps with astonishment. Why were they so shocked? Galen had just proved that the brain, not the heart, controls behaviour.

This might not sound ground-breaking to our modern ears, but the historian Charles Gross describes it as "one of the most famous single physiological demonstrations of all time." Although Galen wasn't the first to recognise the brain's functional importance, he was the first to carry out a public experiment supporting his case. In Galen's time, the 'cardiocentric view' – the idea that thought, mind and soul are located in the heart – remained dominant and would do so for centuries. Its legacy lives on today with sayings such as "learn things by heart".

The pig demonstration reflects the longer story of how we've come to understand the brain – it's a tale of colourful characters, ghoulish experiments and stubborn myths.

Throughout much of history, our understanding of the brain was often more of a philosophical than a scientific pursuit. This is partly because, until the last century, the biological study of our grey matter was mostly dependent on post-mortem investigations of animal brains and bodies, and only more rarely – thanks to a long-running church ban – human brains. It's amazing to think that as late as 1652, the philosopher Henry More wrote that the brain had no more capacity for thought than "a cake of suet or a bowl of curds".



Christopher Wren's highly detailed illustrations complemented Thomas Willis's writings about the brain's anatomy

One of the most influential brain dissectors who helped overturn these beliefs was the English doctor Thomas Willis. He authored the magisterial book *Anatomy of the Brain*, published in 1664. Willis made astute and visionary arguments that complex mental functions are carried out by the cerebral cortex. This part of the brain had long been seen as little more than a useless 'rind' – cortex means 'rind' or 'husk' in Latin.

The continuing lack of scientific knowledge about the brain allowed mistaken theories to survive until quite recently, theories that seem absurd by modern standards. For example, another long-running belief (this one strongly endorsed by Galen) was that the brain pumps 'animal spirits' around the body. Physicians and scientists believed right up until the 18th century that nerves were filled with these animal spirits – bizarre entities that the philosopher René Descartes described as "a very fine wind". The breakthrough that led to this idea being overturned had to do with electricity and specifically the emergence of electrotherapy as a treatment for paralysis.

Public demonstrations again played their part in changing minds. In an ➲

SCIENCE PHOTO LIBRARY, GREG D. NN

This artist's impression of a human brain shows the organ is filled with a stunning array of nerve cells (neurons), each playing its vital role in helping the brain to regulate and control the mind and body.

> "Previously, researchers had to make assumptions. With EEG they could see how different brain regions became more active"

event held in 1803 in London, for example, Giovanni Aldini (nephew of the pioneering anatomist Luigi Galvani) applied electricity to George Forster's brain to show how it caused the muscles of his face to twitch. Forster didn't know much about this – he'd just been hanged for the murder of his wife and child. But for the audience it helped to show how electricity was part of the way that nerves communicate.

Even as the scientific establishment came to recognise the brain's functional significance, however, another mistaken dogma persisted – the idea that mental functions, such as language, are distributed uniformly throughout the cortex rather than being partly localised in specific brain regions.

One historical patient played a particularly important role in helping to overturn this idea. His name was Louis Victor Leborgne, but he was nicknamed 'Tan', because this was virtually the only word he could utter. At autopsy, the French neurologist Paul Broca discovered that Leborgne had highly localised damage to a region in his left frontal cortex, known today as Broca's area, and he inferred that the damaged region must play an important role in speech.

Broca's presentation of Leborgne's case to the Société d'Anthropologie and the Société Anatomique in 1861 was instrumental in convincing the academic community that language function is particularly dependent on the frontal lobes. The historian Stanley Finger describes this moment as a "key turning point in the history of the brain sciences". Patients like Leborgne, with particular mental or physical deficits tied to specific areas of brain damage, have been one of the most important sources of information about the workings of the brain, and this is still true today.

At the end of the 19th century, brain science was focused once again on the perplexing issue of how exactly nerves manage to communicate with each other. While the earlier realisation of electricity's role had helped to debunk the notion of animal spirits, it was clear that there was more to nerve communication. We know today that electrical current along a nerve cell (neuron) causes it to release chemicals across a tiny gap – a synapse – and these chemicals, known as neurotransmitters, are then picked up on the other side by the receiving neuron. In the late 1800s, however, even the best microscopes and staining methods were incapable of revealing the presence of these gaps between neurons. This led the Italian scientist Camillo Golgi and his contemporaries to propose that nerves are fused together – an erroneous idea known as the 'reticular theory' (from the Latin for 'net').

It was the Spanish neuroscientist Santiago Ramón y Cajal who killed off the nerve net idea thanks to his advances in cell staining techniques, which made it clear that neurons are not joined together after all.

Brain activity

In the 20th century, technology began to play an increasingly important role in advancing our knowledge of the brain, particularly by allowing psychologists and neuroscientists to monitor brain activity. In the 1920s, scientists started to use electroencephalography (EEG), which involves recording electricity emitted by the brain through electrodes placed

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TIMELINE

425 BC

The Hippocratic treatise *On the Sacred Disease* states, contrary to the dominant cardiocentric view, that "from the brain and the brain only arise our pleasures, joys, laughter and jests, as well as our sorrows, pains, griefs and tears."

C.130-210

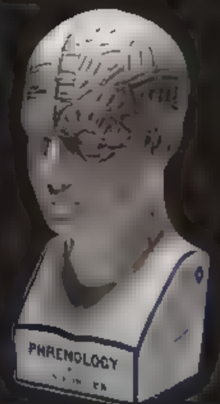
In the 2nd century, the philosopher Galen of Pergamon performs the pig demonstration (see p74), showing that the brain controls behaviour.

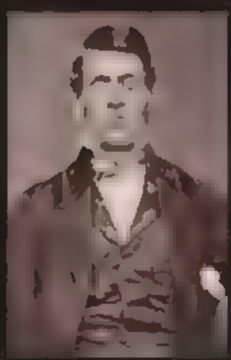
1543

Renaissance anatomist Andreas Vesalius publishes his landmark book *On the Fabric of the Human Body*, showing some of the most detailed dissections of the human brain ever produced.

1830s

Phrenology reaches the peak of its popularity. This was the mistaken idea that psychological aptitudes and personality traits can be discerned from the bumps on someone's skull.

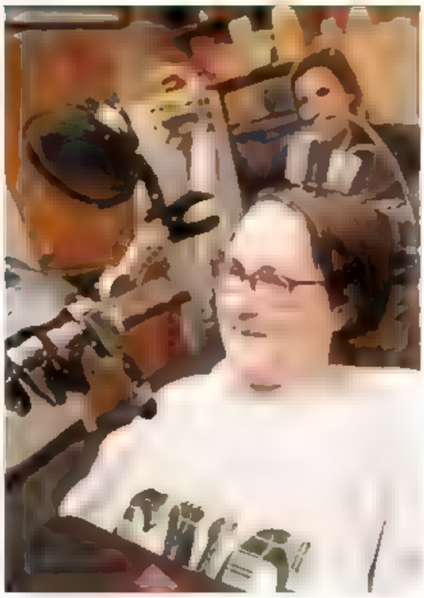




1848

Railway worker Phineas Gage becomes one of the most famous patients in neuroscience after surviving an accident in which an iron rod passes straight through the front of his brain, changing his personality.

Quadriplegic Jan Scheuermann uses thought to control a robotic arm



on the scalp. Previously, researchers had to make assumptions about the location of different mental functions based on the effects of brain injury and by looking for patterns of damage at post-mortem. With EEG they could see how different regions of the brain become more active depending on what the person was saying, thinking or doing. But the problem with EEG is that while it provides good temporal resolution – revealing changes in brain activity from one millisecond to the next – its spatial resolution is crude. This limitation was overcome in the 1960s with the advent of positron emission tomography (PET), which allowed researchers to monitor changing patterns of blood flow in the brain in high resolution. Things progressed even further in the 1990s with the emergence of functional magnetic resonance imaging (fMRI), which also has good spatial resolution but, unlike PET, does not require the injection of a radioactive isotope.

fMRI has had a huge influence on the study of the brain and is now the principal technique used in cognitive neuroscience, merging psychological and biological approaches to brain function. In 2013, a review of the field estimated that over 130,000 fMRI research studies had been published, a figure that will by now be substantially higher.

The next step

Increasingly sophisticated methods for recording and decoding brain activity have helped contribute to important neuroscience breakthroughs in recent years. For example, there has been huge progress in brain-machine interfaces, which enable paralysed people to control computer cursors or prosthetic limbs using thought alone.

Other research has shown that it's possible to use recorded brain activity patterns to communicate with some patients who were previously thought to be in a non-communicative, persistent vegetative state.

But, although we've made great strides in our understanding of the brain, the truth is that we've barely scratched the surface of this highly complex organ. And, sadly, devastating illnesses such as Alzheimer's and motor neurone disease still remain incurable. Let's hope this changes with the record levels of investment being ploughed into new neuroscience research programmes, such as the BRAIN Initiative in the US and the Human Brain Project in Europe. A key player in the latter project is neuroscientist and entrepreneur Henry Markram, who in a TED talk said: "It is not impossible to build a human brain." He made that claim back in 2009 and in the decade since, his project has got a lot closer to reaching that goal. **SF**

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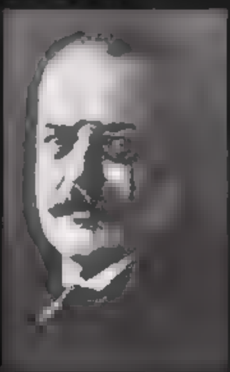
by **DR CHRISTIAN JARRETT**
h_Writer) Dr Jarrett is a neuroscientist and author of Great Myths of the Brain

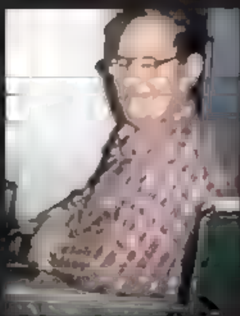
GETTY, ALAMY, SUZANNE CORKIN/ALLEN LANE/PENGUIN BOOKS

1901
Alois Alzheimer, the German psychiatrist, makes detailed notes on Auguste Deter, the first person to be diagnosed with Alzheimer's disease. "I have lost myself," she tells Alzheimer.



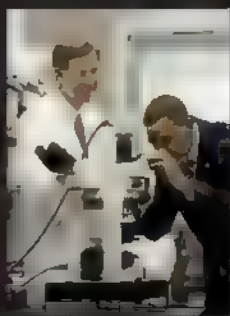
1913
Santiago Ramón y Cajal, the Spanish neuroscientist publishes *Degeneration and Regeneration of the Nervous System*, a book that details his ground-breaking findings on brain injury and recovery. But Ramón y Cajal also claimed, in error, that new neurons do not grow in adult brains.

1953
Patient Henry Molaison undergoes brain surgery for intractable epilepsy. Doctors remove a section of his brain, including the hippocampus, leaving him with profound amnesia. He becomes one of neuroscience's most studied individuals.



1985
The British neurologist **Oliver Sacks** publishes his best-selling book *The Man Who Mistook His Wife for a Hat*. He becomes renowned for chronicling the human element in stories of brain illness and injury. *The New York Times* once called Sacks "The Poet Laureate of medicine".

2013
President **Barack Obama** launches the BRAIN Initiative. "As humans, we can identify galaxies light-years away, we can study particles smaller than an atom. But we still haven't unlocked the mystery of the three pounds of matter that sits between our ears."



GETTY

THE NEXT BIG STEPS FOR

SCIENCE

THE FUTURE OF GENETICS

The latest discoveries and cutting-edge genetic techniques being developed in labs around the world

EPIGENETICS

Dr Nessa Carey reveals how diet, lifestyle and the environment affect your genes

Francis Crick and James Watson became household names for their 1953 discovery of the structure of DNA, a breakthrough that formed the basis for our understanding of how attributes are passed on from one generation to the next. But DNA – the genome – isn't the whole of the story.

Since the 1970s, the role of the 'epigenome' has come under ever-greater scrutiny. The epigenome is the name given to tiny chemical modifications, to DNA and the proteins it wraps around, made by factors such as environment and diet.

So, while your green eyes or dark skin are due to the DNA you inherited from your mother, your wiry build could have something to do with how your grandmother was living while she was carrying her.

Does this mean that the Darwinian model of evolution is dead? Of course it doesn't, even though there are now epigeneticists who refer to themselves as neo-Lamarckians (see page 72). Most of the time, eggs and sperm are protected from epigenetic changes to the environment, and relatively few newly established modifications are likely to make it through to the next generation. Even when they do, the modifications and the effects they cause tend to die out within a few generations.

Despite this, there is an increasing and facile tendency to 'blame' epigenetic inheritance for current problems, especially with respect to the human obesity epidemic. Fascinating though this field is, it's not a get-out. The most important things that are happening to your health are happening here and now: no one gains weight in 2015 just because their grandad had a fondness for doughnuts in the 1960s.

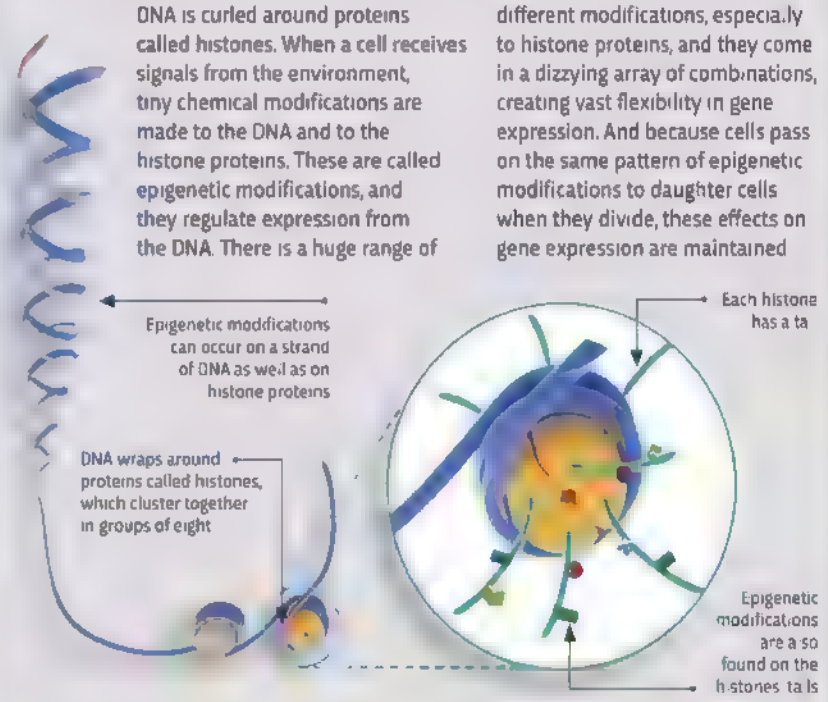
DR NESSA CAREY

Dr Carey is a molecular biologist and author of The Epigenetics Revolution

HOW IT WORKS

How epigenetic modifications are passed on to our kids

DNA is curled around proteins called histones. When a cell receives signals from the environment, tiny chemical modifications are made to the DNA and to the histone proteins. These are called epigenetic modifications, and they regulate expression from the DNA. There is a huge range of different modifications, especially to histone proteins, and they come in a dizzying array of combinations, creating vast flexibility in gene expression. And because cells pass on the same pattern of epigenetic modifications to daughter cells when they divide, these effects on gene expression are maintained



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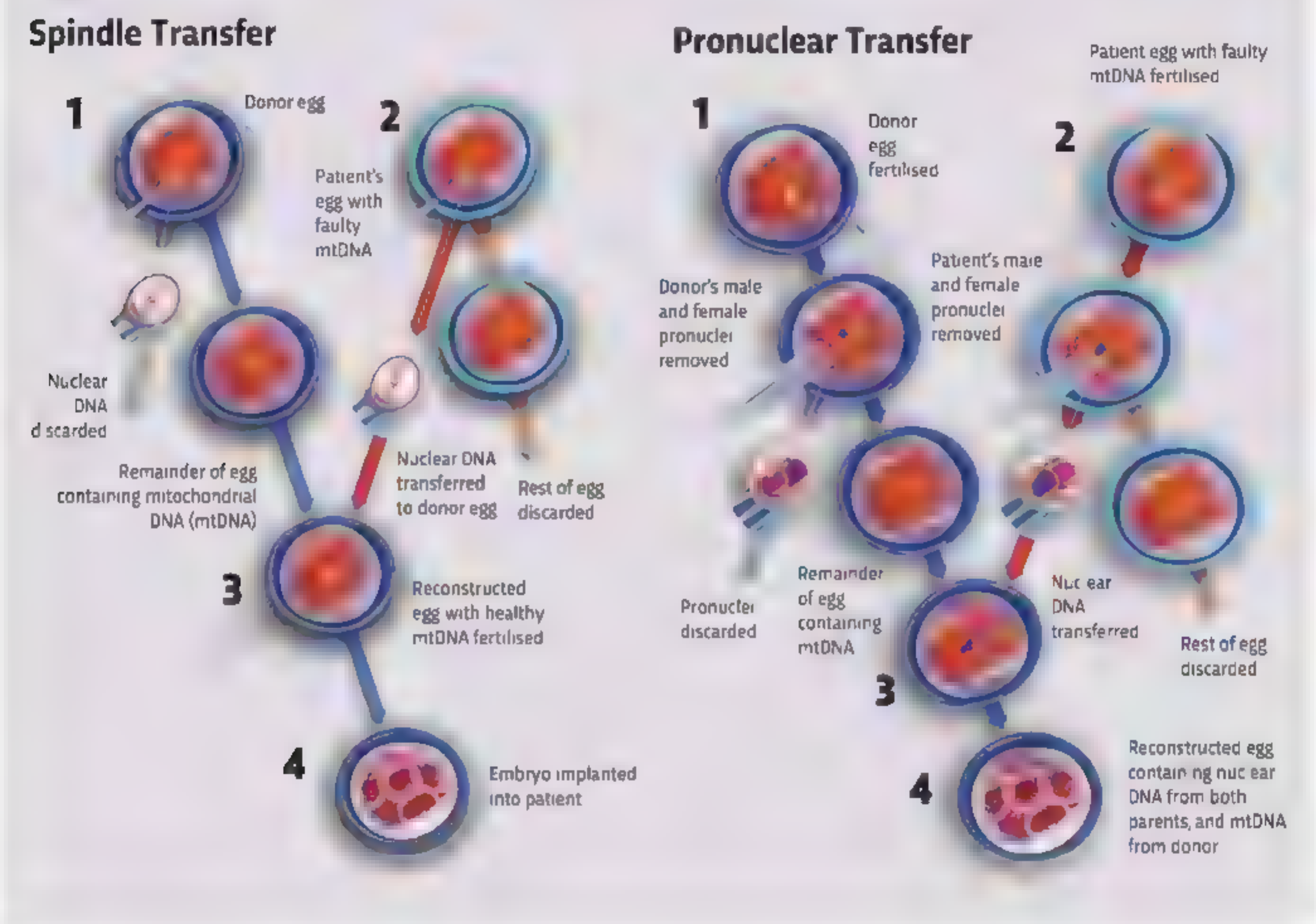
MAKING GM BABIES

There are several techniques for creating a baby from three parents. Here are two of them



GM BABIES

Zoe Cormier looks at children with three parent families

Back in February 2015, Parliament voted to amend the 2008 Human Fertilisation and Embryology Act to allow 'three-parent IVF' for families that carry mitochondrial diseases. These diseases are coded in the genes and are passed from mum to child via the mitochondrion, the 'battery' of a cell.

Human egg cells contain mitochondria the way most cells do, but sperm cells only have them in their tails. During fertilisation, the head of the sperm, which contains its genes, is inserted into the egg. The tail of the sperm – and therefore its mitochondria – is left behind. This is why all of us only inherit our mitochrondrial DNA from our mothers.

Malfunctioning mitochondria can produce a wide variety of illnesses for which we have no cure. It is estimated that one in 200 children in the UK carries some form of genetic mutation that could lead to mitochondrial disease at some point in life. Every year, one in 6,500 babies is born with a mitochondrial condition so severe that they will not reach adulthood.

Altered embryos

The technique that was legalised in the UK at the beginning of 2015 will allow a mother to give birth to a baby that is genetically hers, but there will not be the risk of it inheriting mitochondria with dangerous mutations. The process is known as 'mitochondrial donation' or 'mitochondrial transfer'.

A mother-to-be carrying faulty mitochondria can opt to have her nuclear DNA removed from her eggs and implanted into a donor egg carrying healthy mitochondria. The egg is then fertilised with sperm from the father before being implanted into the mother's uterus for pregnancy to continue as usual.

On 25 July 1978, Louise Brown – the first test tube baby – was born in Oldham General Hospital. At the time, concerns were raised about 'Frankenbabies' and 'playing God', and some members of the public subjected the parents to hate mail. Today, however, more than five million children have been born via IVF.

Ultimately, doctors are confident that this new technique will follow in the path of IVF to become a routine treatment that could transform lives.

by ZOE CORMIER (@zoecormier)
Zoe is a freelance science journalist and author of Sex, Drugs & Rock n Roll: the science of hedonism

GENE EDITING

Dr JV Chamary looks at a new molecular biology technique

The most powerful new technique in molecular biology is the CRISPR-Cas9 system – known as 'CRISPR'.

CRISPRs (Clustered Regularly Interspaced Short Palindromic Repeats) are sequences of DNA letters, first discovered in *E. coli* in 1987. A decade later, researchers revealed that CRISPRs form part of an anti-viral defence system used by bacteria and other microbes: after a virus invades a cell, enzymes cut and paste bits of the viral genome between CRISPR sequences in the cell's DNA. This leaves a genetic memory for an RNA 'guide' that an enzyme called 'Cas9' uses to recognise and destroy viral DNA, should an invader return. In 2012, bioengineers showed that the RNA guide could be reprogrammed to target any DNA sequence.

One of CRISPR's most useful applications is gene therapy – to treat or even cure a disease by correcting a patient's DNA. In traditional gene therapy approaches, a vector such as a harmless virus is used to deliver a working gene to compensate for a defective copy. This inserts new DNA at a random location in the human genome, whereas CRISPR can also remove a person's faulty gene at a specific place. Researchers have already used CRISPR to fix conditions like inherited liver disease in mice.

Unlike most gene-editing techniques, CRISPR is revolutionary because the technology is precise. It's also quick, cheap and easy to use – so simple that even amateurs can use it, including so-called 'biohackers'. Biohacker labs around the world, such as the London Biohackspace, might one day use CRISPR editing for their do-it-yourself biology projects.

Playing safe

Anyone who tinkers with nature can be accused of 'playing God'. It's understandable that critics might worry about amateurs meddling with organisms they don't understand. But CRISPR is merely a tool – you still have to have an idea of what genes you want to turn on and off. Plus, biohacking is limited by the resources available to a typical DIY bio lab. **SF**

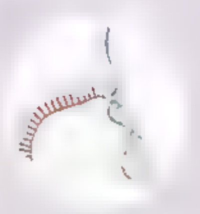
By DR JV CHAMARY
Dr Chamary is a biologist and author of 50 Biology Ideas You Really Need to Know

Biohackspace director Ilya Levantis (far right) discussing future plans with artist Lena Asai (centre) and other members

CRISPR

A powerful DNA editing technique

1



Scientists design a 'CRISPR' made from RNA. It includes a series of letters that matches a unique DNA sequence within an organism's genome

2

The CRISPR molecule is attached to 'Cas9' (shown here in beige). This is an enzyme that uses its RNA 'guide' to recognise the target DNA sequence

3

The CRISPR-Cas9 tool cuts the strands of the target DNA's double helix, then the cell's repair machinery will fix the damage – minus the old DNA sequence.

4

The CRISPR technique can be used to delete unwanted DNA, or to find and replace a sequence by adding genetic material – such as a new gene

JV CHAMARY

6 SYNTHETIC BIOLOGY BREAKTHROUGHS THAT COULD CHANGE THE WORLD

From new cancer treatments to DNA-based computers, *Dr Adam Rutherford* reports on how biological engineering could power a technological revolution

GETTY

> "NASA has designed a biocapsule out of carbon nanofibres, which will be implanted underneath the skin of an astronaut"

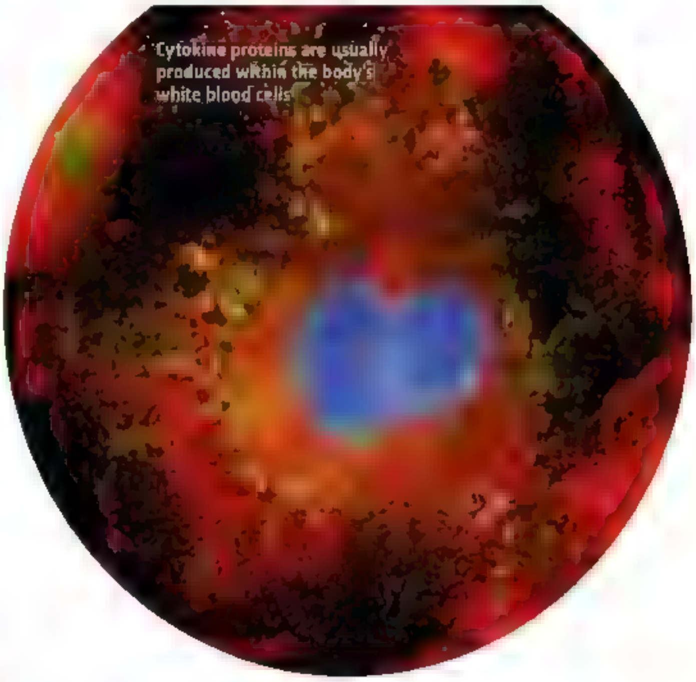
1. IMMUNITY TO RADIATION

Shielding astronauts from health hazards in space

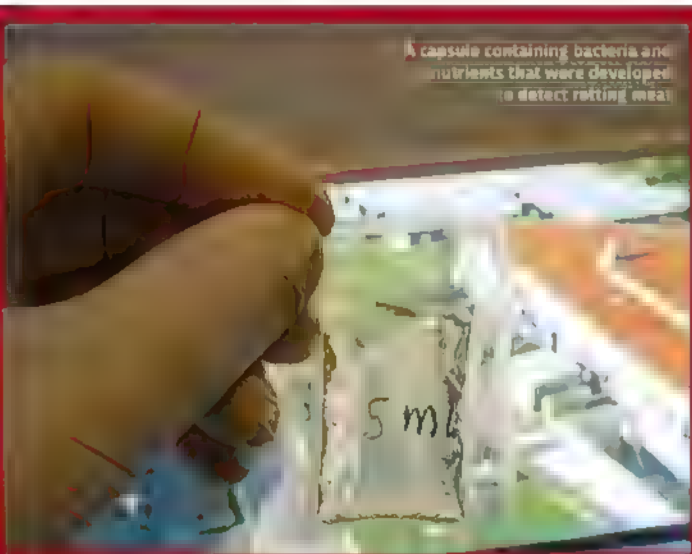
At Ames Research Centre in Silicon Valley, NASA scientists are looking at how to equip astronauts to endure the extreme hostility of space.

One of the biggest barriers to human exploration is that with current propulsion technology, trips will take years. That exposes astronauts to mutagenic and life-threatening levels of solar radiation and cosmic rays. Radiation slices up DNA, which can cause all sorts of problems, not least cancers. But shielding is heavy, making it costly to launch off Earth.

At Ames, they are designing a synthetic biological circuit that will produce cytokines – the body's own defences against radiation damage – when it meets space radiation. But where do you put it? Having free-floating synthetic bacteria in your body is not a good idea. So NASA has designed a biocapsule out of carbon nanofibres whose pores are too small to let the bacteria escape, but big enough to let the cytokines they produce out. This capsule will be implanted underneath the skin of an astronaut.



Cytokine proteins are usually produced within the body's white blood cells



A capsule containing bacteria and nutrients that were developed to detect rotting meat

2. CELLULAR TOOLSETS

Synthetic biologists playing with building bricks

Anyone who travels knows what a pain it is to have the right power adaptor. In electronics, parts were standardised decades ago so that every time you needed a diode you didn't have to invent it.

Genetic engineering has been slow to catch up, but now the BioBricks Foundation is striving to make synthetic biology more productive and creative by making the parts fit together easily. And nowhere is the commodification of biology more apparent than in the International Genetically Engineered Machine (iGEM) competition. The challenge is to design synthetic life using only the parts available from a 'shopping catalogue' of synthetic biology. Each part is free and, in principle, standardised to fit together with the others.

In 2012, one team created a bacterium that changes colour in the presence of rotting meat.

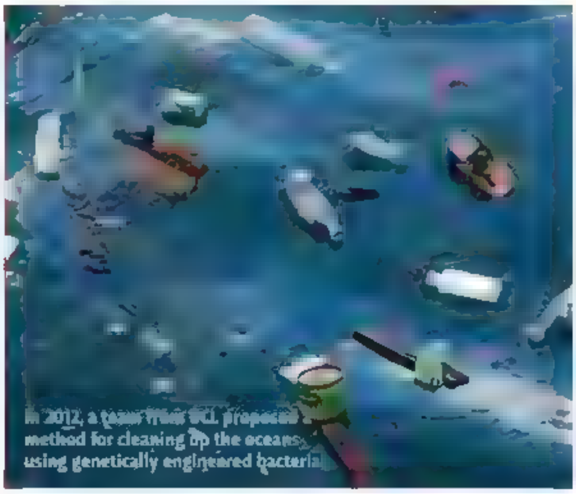
3. OCEAN CLEANERS

Engineered microbes to clean the seas

The 2012 iGEM runners-up from University College London (UCL) came up with the idea of cleaning up the oceans by assembling a plastic island. There are millions of tonnes of plastic rubbish floating around in the oceans – mostly as billions of tiny fragments. These can accumulate in ocean gyres – areas where currents meet, causing a vortex – and enter the food chain, often killing wildlife.

UCL's team designed salt-tolerant, buoyant bacteria that would identify plastic fragments and either degrade them or aggregate them into lumps, which could be collected into an island they called – in James Bond villain style – the Plastic Republic.

With safety in mind and to ensure no environmental contamination, the bugs were engineered with a 'kill switch', so that their DNA was not able to spread to other organisms.



In 2012, a team from UCL proposed a method for cleaning up the oceans using genetically engineered bacteria

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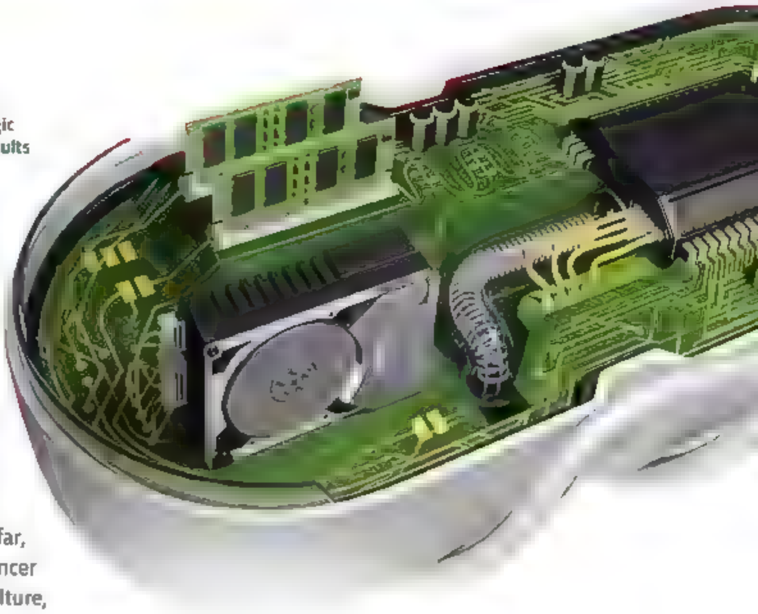


A team at MIT has built DNA circuits that can perform logic operations and store the results

4. CANCER ASSASSINS

Genetic circuits to eradicate cancerous cells

The most effective ways to treat cancers are still chemotherapy and radiotherapy. Although these techniques are getting more precise in targeting malignant cells, they still kill many healthy cells, making the patient sick during their treatment.

Back in 2011, Ron Weiss and his team at MIT designed a genetic circuit that slots into a harmless virus, which then infects a cell. Once in there, it effectively asks the cell five biological questions. If the answer to any of these molecular queries is negative, the circuit deactivates. If all five answers are positive, the cell is identified as cancerous and the circuit activates the cell's own suicide programme. Compared to the blunderbuss approach of radiotherapy, this is a sniper. So far, this only works in one type of cancer cell, called HeLa, and only in a culture, not yet in animal models.

More recently, researchers at the University of California and MIT have come up with another strategy. They engineered a bacterium to produce cancer drugs and then self-destruct, releasing the drugs at a tumour. The technique was tested on mice and found to reduce tumour size.

HeLa cancer cells in culture can be destroyed by a genetic circuit

5. BIO-COMPUTING

Biological circuits could be the future

Lifeforms are much more complex than the most powerful computers – but noisier too, meaning that the underlying logic is not always linear, clean or obvious. Part of the work of the synthetic biology movement has been to strip out the noise of biological systems and reduce them to their component parts, ready for re-building.

The result could be super-compact systems that can store information for tens of thousands of years. Back in 2013, there were a couple of high points in the computerisation of biological circuits. In February, MIT scientists programmed a circuit out of DNA that could store memory for up to 90 cell generations – roughly nine days – using logic functions akin to those in electronics. A month later, another team published a system of DNA that works like a transistor – the essential component behind all modern electronics.

In 2016, MIT scientists created a programming language, allowing them to rapidly design complex, DNA-encoded circuits that give new functions to living cells.

6. ANTI-MALARIAL WEAPONS

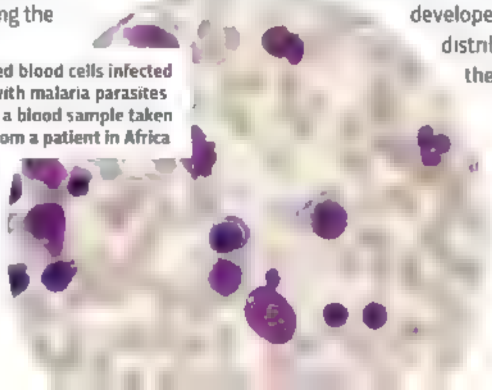
More effective malaria drugs are on the horizon

Malaria has killed more humans than anything else in history. Up to a million people still die from the disease each year and the WHO estimates that the financial burden of treating malaria in sub-Saharan Africa since the 1960s has been hundreds of billions of dollars.

Since the 17th century, we've tackled it with a series of treatments, such as quinine and chloroquine with limited success. The problem with this kind of serial medical monogamy is that the parasites evolve resistance. For that reason, the most effective treatment today is a cocktail of drugs, including the key ingredient artemisinin. It's an extract from a sweet wormwood, an Asian shrub that's been used in folk medicine for centuries. But wormwood is finicky to grow and over the last few years the artemisinin market has been subject to boom and bust cycles, and hence fluctuating supply and costs.

Enter Jay Keasling. While trying to design a genetic circuit that would produce diesel in his labs at the University of California, Berkeley, one of his students noticed that a by-product was closely related to artemisinin and they decided to follow this up. Built from 12 genes from three different organisms, the first successful cellular synthetic artemisinin producer was published in 2006.

After major investment from The Bill and Melinda Gates Foundation (as well as a number of other investors), the drug was developed. Recently, market forces have hindered the distribution to malaria zones, but this story marks the first great product of synthetic biology. The revolution has begun. **SF**



Red blood cells infected with malaria parasites in a blood sample taken from a patient in Africa

by DR ADAM RUTHERFORD
(@AdamRutherford)
Dr Rutherford presents Radio 4's Inside Science

THE NEXT BIG STEPS FOR SCIENCE

SEARCHING FOR DARK MATTER

For decades, top astronomers have been on an enormous treasure hunt for the Universe's most mysterious substance. But if we can't see it, how on Earth do we know it even exists? *Colin Stuart* explains

Q Why do scientists think that dark matter exists?

A The first clues that everything in the Universe was not as it seemed came in the 1930s. Swiss-American astronomer Fritz Zwicky was looking at a group of galaxies and working out how fast the individual galaxies were moving. To his surprise, he found them careering around at speeds far greater than he expected. In fact, they were moving so fast that they should have quickly dispersed, breaking away from the gravity of everything else in the cluster. Except they weren't. Zwicky was forced to surmise that there must be more stuff in the cluster that was boosting its overall gravitational pull and keeping the galaxies tied together. The discrepancy wasn't small either. He estimated there was 400 times more matter present than he could see. At a loss to explain what this mysterious material was, he called it 'dunkle materie' – German for dark matter.

At the same time, Dutch astronomer Jan Oort was forced to invoke something similar. He was looking at the stars orbiting near the edge of the Milky Way. He expected to find that the further he looked from the galactic centre, the slower the stars would be rotating around it. This idea isn't dissimilar to our Solar System: the further a planet is from the Sun, the longer it takes to orbit it. But that's not what Oort found. The outer stars were zipping about faster than they should be. In order to explain why they stayed bound to the Milky Way despite their lofty speeds, he supposed there was some invisible material with gravitational power spread throughout the Galaxy. By 1980, American astronomer Vera Rubin had spotted the same effect in around 100 other galaxies. Whatever this invisible stuff was, it was widespread.

Today, an effect known as gravitational lensing provides even more evidence to suggest there is something strange going on. If we see a large amount of mass, say a cluster of galaxies, move in front of a distant light source, then the foreground object is able to bend the light from the background object around it. This light creates a series of arcs that can join together to form what's known as an 'Einstein ring'. The more mass there is, the greater the amount of bending. Yet there is often not enough visible mass in the cluster to account for the amount of bending we observe. Again, there must be extra mass that's hidden from view.


Vera Rubin studied a large number of galaxies and found that the effects of dark matter are widespread

Q What do scientists think dark matter is?

A Physicists have a cookbook for the Universe known as the Standard Model of particle physics. By using its recipes, they can account for the behaviour of forces and the way particles interact with one another. This model has been validated many times over, including by experiments at CERN's Large Hadron Collider. The book's final missing page was the recently discovered Higgs boson. And yet there is nothing within those recipes that allows physicists to cook up anything with the observed behaviour of dark matter. It has to be able to interact with normal matter via gravity – and yet in order to remain

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IN A NUTSHELL

Around 85 per cent of the mass of the Universe is made up of dark matter that can't be directly observed. It does not emit light or energy, and yet often the gravity in a particular location seems stronger, suggesting some invisible matter.

> "In an attempt to explain this behaviour, physicists have come up with a new type of particle: WIMPS"

hidden, it cannot interact with light. In an attempt to explain this behaviour, physicists have come up with a new type of particle: Weakly Interacting Massive Particles (WIMPs). They are 'weakly interacting' because they don't interact with light and 'massive' as they interact via gravity.

When astronomers run computer simulations of a Universe that evolves with dark matter in the form of WIMPs, they get a structure that is a pretty solid match for the distribution of galaxies that we see today. A theory for physics beyond the Standard Model called supersymmetry also seems to fit with this picture.

Other explanations have been considered in the past, including MACHOs. Standing for MAssive Compact Halo Objects, the idea is that there are big objects, such as black holes, ghosting unseen through the Milky Way. When we add up all the mass we can see, we aren't including them, hence why we underestimate the mass of the Galaxy.

Q What are scientists doing to find dark matter?

A How do you find something that is, by definition, hidden from view? You certainly can't see it. To make things worse, WIMPs are so ghostly that they almost always pass straight through normal matter – including any detector you build to snare one.

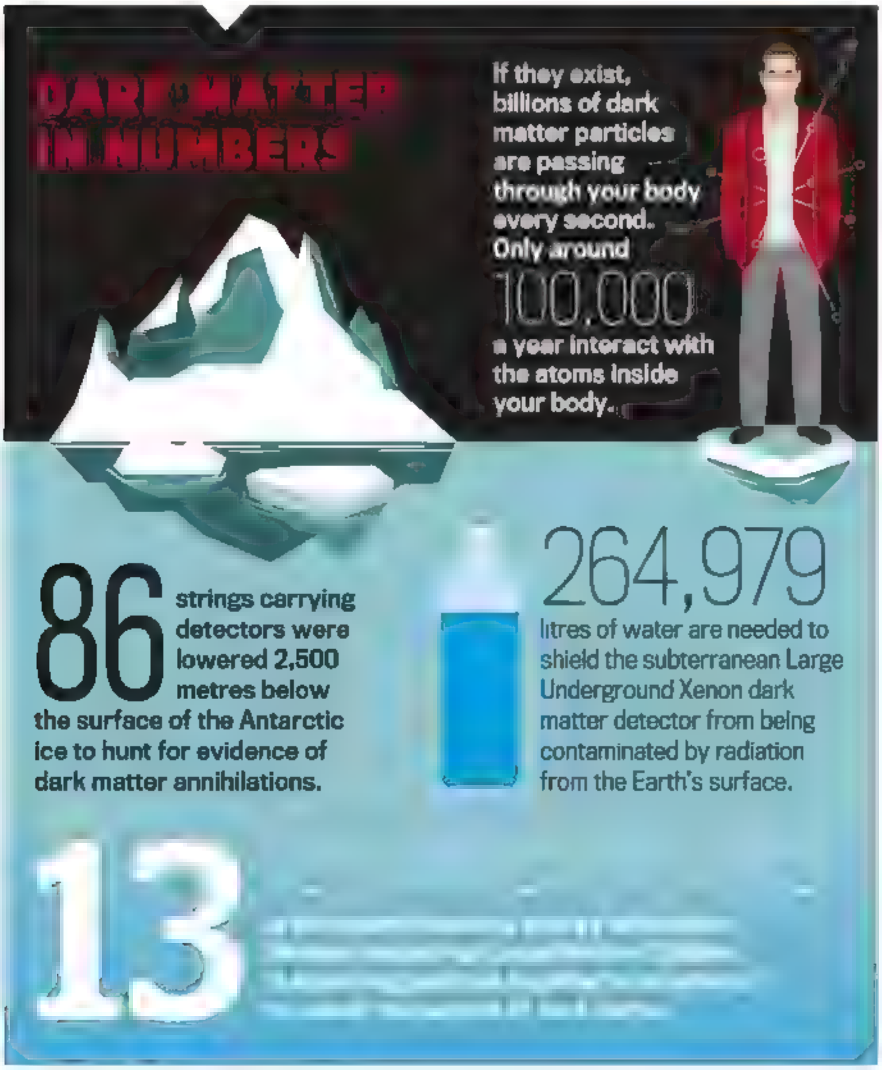
To put it into perspective, dark matter is so abundant that billions of dark matter particles are streaming unhindered through you every single second. And yet, on average, in any five-minute period, only one of these dark matter particles interacts with an atom of normal matter in your body.

This idea that dark matter particles do occasionally deign to interact with normal matter is the basis for the Large Underground Xenon experiment deep under the surface of South Dakota. Scientists have commandeered an abandoned gold mine and set up a dark matter detector 1.6km down. Consisting of 370kg of liquid xenon shielded by 264,979 litres of water, it is designed to pick up the occasional WIMP interacting with the xenon. Should a WIMP recoil off a xenon atom, the atom is accelerated through the liquid, causing a flash that can be picked up by the surrounding banks of super-sensitive cameras.

Scientists might also be able to detect dark matter when it interacts with itself in a process known as annihilation. When this happens, it is thought a cascade of 'normal' particles is produced and we should be able to pick that up. One such experiment is the Alpha Magnetic Spectrometer (AMS-02) currently strapped to the International Space Station. It is trying to pick up evidence of atomic shrapnel coming from WIMP annihilations near the galactic centre.

The Sun could help too. As the biggest thing in the Solar System it should be acting as a giant cosmic vacuum cleaner, sweeping up dark matter particles as it treks through the Galaxy. Some of the dark matter particles should annihilate inside the Sun, producing a stream of normal particles. Unfortunately, the Sun is so dense that almost all of these daughter particles remain trapped inside. However, one type of particle – neutrinos – would make it out and travel across space to us. Experiments such as IceCube, stationed on Antarctica, are set up to gather these tell-tale signals.

Then there is the Large Hadron Collider (LHC). On 5 May 2015, the experiment began smashing protons together after a two-year shutdown



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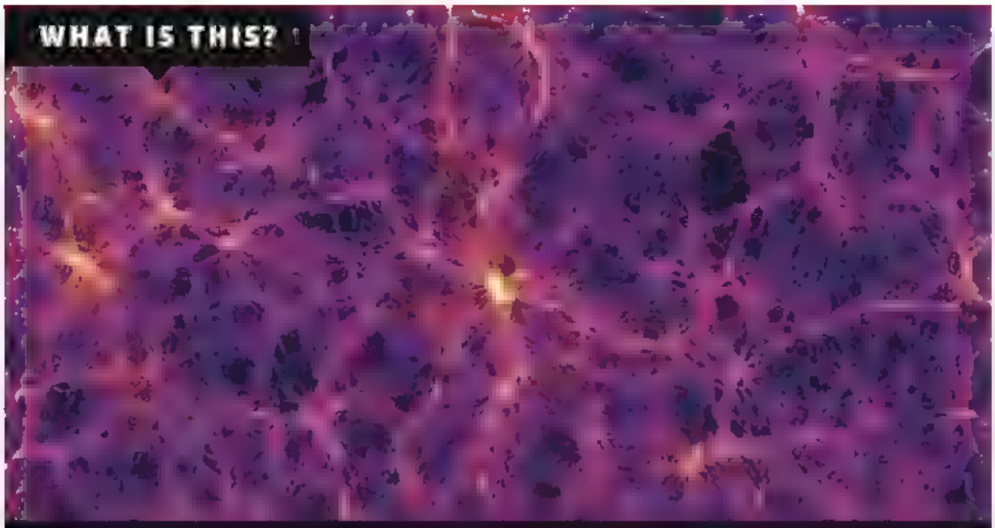

When astronomers look at the Universe on the largest scales, they see huge clusters of galaxies strung out on long filaments, which border enormous cosmic voids. They explain this distribution by suggesting dark matter provides a 'scaffold' by drawing ordinary matter together with its gravitational influence.

designed to boost the machine's power. Hopefully, by colliding particles with more energy than ever before, nature may begin to reveal more secrets of its inner workings.

Q Could dark matter be something else?

A So far we've been assuming that dark matter is tangible, something that truly exists. But what if it doesn't? What if it's a phantom – a symptom of the fact that we don't understand gravity properly? That's exactly what proponents of a theory called Modified Newtonian Dynamics (MOND) advocate.

Remember, one of the original reasons dark matter was introduced was to account for the fact that stars in the Milky Way don't slow down the further they are from the galactic centre, unlike the planets of our Solar System. But what if there is one rule for gravity on small scales (such as a solar system) and another for large scales (like a galaxy)? While Newton's laws of gravity allow us to send people to the Moon or spacecraft to the planets, stretching those rules to regions to where they don't apply might explain why we're puzzled by the strange motions of stars.

The idea was first put forward by Israeli physicist Mordehai Milgrom in 1983. He suggested that the strength of gravity could become stronger where acceleration levels are small. These ideas can help to explain some details about how galaxies work in ways that the dark matter theory cannot. But there is currently no reason to suspect that gravity behaves differently on different scales

Q Has dark matter got anything to do with dark energy?

A No. Dark energy is the name given to the mysterious entity thought to be accelerating the overall expansion of the Universe – a sort of anti-gravity. In contrast, dark matter can be thought of as gravitational glue that helps bind galaxies and clusters of galaxies together. We're literally in the dark as to what they are.

Q How much dark matter is there?

A Dark matter completely dominates the ordinary matter of which people, planets and stars are made. Our Milky Way is thought to be about 90 per cent dark matter and only 10 per cent 'normal' matter (baryonic matter). Of all of the matter in the Universe, 85 per cent is dark matter and only 15 per cent is baryonic.

But, according to Einstein's famous equation $E=mc^2$, mass and energy are two sides of the same coin. This leads cosmologists to often talk about the mass-energy of the Universe – all the mass and all the energy put together. In these terms, the Universe is 68 per cent dark energy, 27 per cent dark matter and just 5 per cent atoms. If we discount the energy part, the numbers revert to above – 85 per cent dark matter, 15 per cent baryonic matter. **SF**

by COLIN STUART @skyponderer
Colin is a science writer and author, and a Fellow of the Royal Astronomical Society

NEED TO KNOW

Understand dark matter with these terms

ANNIHILATION
The process by [illegible] particles come togeth[illegible] made of [illegible] attempting to detect this with various experiments around the world [illegible]

GRAVITATIONAL LENSING
A prediction of Einstein's General Theory of Relativity [illegible] ways that mass bends [illegible] ten see more [illegible] the amount of [illegible]

NEUTRINO
[illegible] almost massless particle created by nuclear reactions inside the Su[illegible] Additional neutrinos may be created by dark matter annihilations and detecting [illegible] could be a big [illegible] breakthrough

STANDARD MODEL
The recipe book that particle physicists use to explain a lot of the subatomic world. It contains rules regarding [illegible] interac[illegible] and li[illegible]

SUPERSYMMETRY
An idea that [illegible] particle has a [illegible] symmetric partner [illegible] The lightest of these [illegible] symmetric particles co[illegible] dark matter

THE EXISTENCE OF BLACK HOLES

The idea of 'dark stars' that gobble up any planets in their path dates back to the 18th century. But, as *Brian Clegg* explains, it wasn't until 1964 that hard evidence of their existence emerged

Black holes have escaped from astrophysics into the everyday imagination. But there are gaps in our knowledge of their nature and even, possibly, their existence.

Black holes were born from theory, not observation. We have known about conventional stars for as long as we've been able to look at a clear night sky but no-one ever saw a black hole. Instead, they were predicted to exist at a time when there was no way of checking whether there was any such thing out there. And that prediction happened not once, but twice.

The first inspired thinking on the matter was in the 18th century. The man who dreamed up what he called 'dark stars' was John Michell, a scientist who became a clergyman. It was from his rectory that he came up with the concept, combining two key ideas of the latest science at the time.

One was escape velocity. Michell knew that when a bullet is shot straight up into the air, it has just two forces acting on it once it leaves the gun: air resistance and gravity. As it gets higher, both of these forces weaken. The air gets thinner and, as Newton had made clear, gravity's attraction drops off with the square of the distance between the centres of the bodies involved – in this case, the bullet and the Earth

Ole Rømer calculated a speed for light, settling the dispute over whether it travelled instantly or just very quickly

A typical bullet from the black powder guns of Michell's day could travel as fast as 300 metres per second. But despite this impressive velocity, the forces acting to slow it brought the bullet back down to Earth. Michell, though, knew that a bullet travelling about 37 times faster would be able to overcome the Earth's attraction and fly off into space – it would have achieved escape velocity. He combined this idea with a discovery from the 1670s, when Danish astronomer Ole Rømer realised that an apparent variation in the timing of Jupiter's moons was caused by the varying time that light took to reach us from the planet.

Light conversation

Ever since ancient times, there had been arguments over whether light travelled instantly or just extremely quickly. Rømer found evidence for a measurable speed, as the changing relative positions of Jupiter and Earth in their orbits varied the time that light took to reach us. He calculated the speed of light to be around 220,000km/s. In the following 100 years, this figure was measured more accurately so that Michell was working with something closer to our current 300,000km/s. But the specific value didn't matter – the point was that light had a speed.

Combining the two concepts of escape velocity and light having a finite speed, Michell wondered what would happen if a massive star had an escape velocity that was above the speed of light. The more mass in a body, the higher its escape velocity. Therefore, in principle, there could be a star so vast that even light would not escape from it. Such a 'dark star' would have to be immense. Even though the escape velocity from the surface of the Sun, for instance, is over 600km/s, it is still far lower than the speed of light. Michell's theory was

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Computer rendering of a supermassive black hole. Jets of matter are emitted at right angles to the accretion disc

IN A NUTSHELL

Studying black holes is particularly difficult as they cannot be seen directly. The work of eminent scientists like Albert Einstein, Kip Thorne and Stephen Hawking has helped increase our understanding, but many gaps in our knowledge still remain to this day.

> "When matter is dragged into a spinning hole, it should produce a glowing 'accretion disc' and distinctive 'jets' from the poles"

based on an incorrect assumption – that light was made up of normal particles that could be slowed down like any other projectile by gravity. But the idea of these mysterious 'dark stars' faded into history.

Fast forward to the 20th century and Karl Schwarzschild revived the theories in the heat and horror of World War One. It was 1915 and the 41-year-old German physicist had volunteered to join up with the German army. Somehow, perhaps as a distraction from the devastation around him, he found time to think about Einstein's elegant equations and his brand-new theory of General Relativity. Einstein's equations are too complex to provide a universal solution, but Schwarzschild solved them for the special case of a spherical body that was not spinning.

It emerged from the mathematics that, if all the mass of that body was crammed into a sphere of a size now called the Schwarzschild radius, the distortion in space-time would be so great that light from the object would never escape. Anything closer than a sphere around the body of that radius would travel through a surface of no return – the black hole's event horizon.

The most obvious source of such a body would be a collapsing star. In normal operation, a star's nuclear reactions fluff it up against the pull of

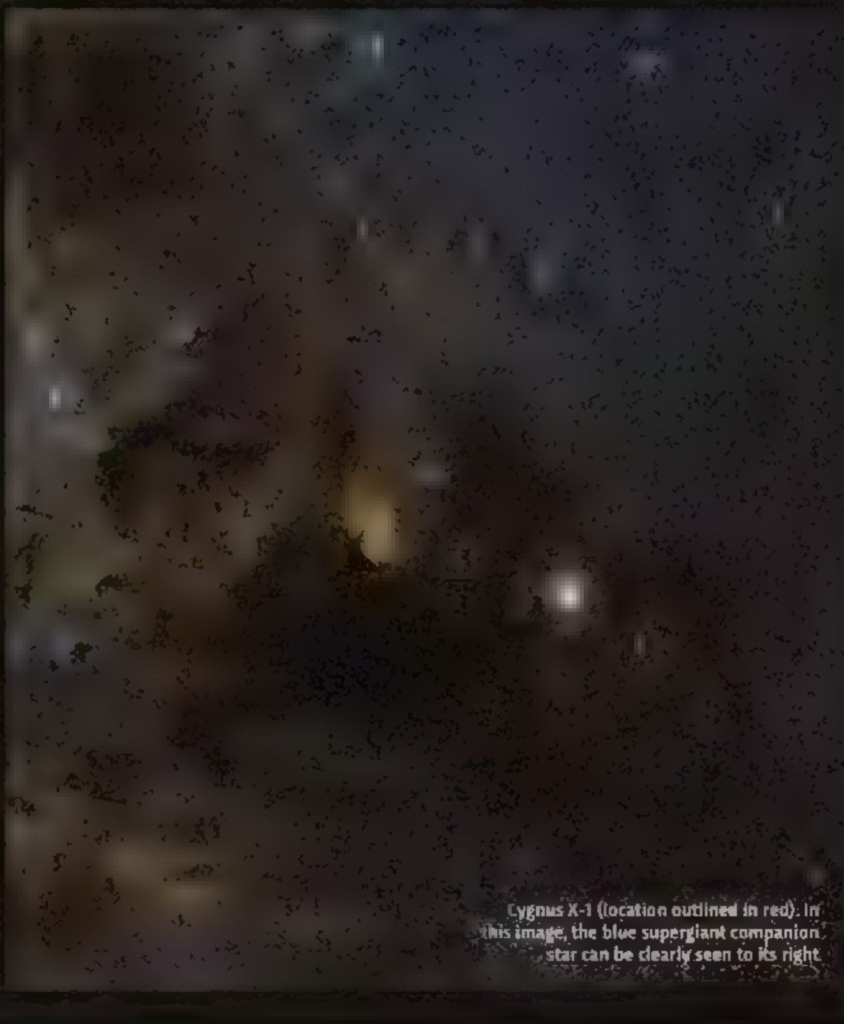
THE KEY EXPERIMENT

Black holes are tricky to study as even the closest one lies many light-years away, but scientists can identify candidates by observing their X-ray emissions

Performing experiments on black holes is a non-starter, as the nearest candidate so far detected is around 3,000 light-years away.

Official confirmation of Cygnus X-1, the first significant candidate found, took a number of years as no single observation was capable of establishing such a remarkable find.

In 1964, a rocket launched from the White Sands Range in New Mexico discovered a strong X-ray source in the constellation of Cygnus. Also in 1964, two sub-orbital rockets mapped out X-ray sources, pinning down the location of Cygnus X-1. In 1971, observations by the Uhuru X-ray satellite telescope showed that the Cygnus X-1 source underwent rapid oscillations, suggesting it was a compact object that was smaller than the Sun. That same year, radio telescope observations linked the X-ray source to the star HDE226868. This blue supergiant would not itself produce X-ray emissions, implying that it had a companion. Also in 1971, astronomers at the Royal Greenwich Observatory and Toronto's David Dunlap Observatory made further observations of HDE226868. They confirmed that it was in a binary with a massive but compact object. And, in 1972, Charles Bolton at Toronto was the first to state definitively that this object was a black hole. This view was generally accepted by 1973.



Cygnus X-1 (location outlined in red). In this image, the blue supergiant companion star can be clearly seen to its right

NASA/CHANDRA

gravity. But once those reactions start to fade, matter in the star can collapse. The expectation is that this collapse would be halted by a quantum effect called the Pauli exclusion principle, forming an intensely dense neutron star. If the star were massive enough, though, exceeding about three times the mass of the Sun, the exclusion principle should be overcome and the collapse would be unstoppable. In principle, the material in the black hole would continue to collapse all the way to a dimensionless point – a 'singularity' with infinite density and a force of gravity that headed off to infinity as it was approached. In reality, we don't know what would actually happen, because the singularity is an admission that our physics has broken down. For a good time after Schwarzschild, black holes were purely theoretical.

Or at least collapsed stars were, as they were yet to receive their more intriguing moniker.

Down the hole

The term 'Black hole' is often ascribed to the American physicist John Wheeler, but its origins are shrouded in mystery. The term was first reported at an American Association for the Advancement of Science meeting in January 1964. It's not certain who used it, but Wheeler soon popularised it. It might seem that searching for black holes would be a waste of time. How do you see something that doesn't give off light? But, as the physics of black holes developed, scientists realised that indirect routes were available.

As astronomers can't see the hole itself, they need to look for its side effects. When matter is dragged into a spinning hole, it should produce an 'accretion disc', glowing brightly as a result of friction produced by the spinning matter – and would also generate distinctive 'jets' from the poles. Then there are the gravitational effects. We might see nearby bodies influenced by the black hole. This is a venerable technique and was used in the past to infer the existence of Neptune. Astronomers studied the way the orbits of the other planets

ALAMY X2 GETTY X3

CAST OF CHARACTERS

Five giants of physics who made invaluable contributions to our understanding of black holes

JOHN MICHELL (1724-1793)
Michell was born in Nottinghamshire and spent his academic life in Cambridge working on geology, gravity, magnetism and astronomy. After his marriage in 1764 he spent the rest of his life as a clergyman, most notably at Thornhill in Yorkshire. Here he continued with his scientific work from 1767 until his death in 1793

KARL SCHWARZSCHILD (1873-1916)
Schwarzschild was a German physicist and astronomer who was born in Frankfurt. He worked as a professor for several years in Göttingen, before moving on in 1909 to become director of the town's observatory. He subsequently headed up the Potsdam Astrophysical Observatory. He volunteered for the German army in 1914 and died of a skin disease in 1916

ALBERT EINSTEIN (1879-1955)
German-born Einstein is best known for his theories of Special Relativity and General Relativity, laying the foundations of quantum theory. Via Belgium and the UK he moved to the US in 1933 to escape Nazi Germany and took up a position at the Institute of Advanced Study in Princeton

KIP THORNE (1940-)
Thorne is an American astrophysicist whose studies of General Relativity have resulted in a wide range of predictions on black holes, wormholes and time travel. Thorne was consultant to the best cinematic representation of a black hole to date, the 2014 film *Interstellar*

STEPHEN HAWKING (1942-2018)
Cambridge-based Hawking is among the most famous physicists thanks to his bestselling book *A Brief History of Time* and for defying the onset of motor neurone disease to continue working into his 70s. His work has largely involved the General Theory of Relativity and cosmology


On 10 April 2019, astronomers using the Event Horizon Telescope unveiled the first image of the silhouette of a black hole, spotted at the centre of the galaxy M87

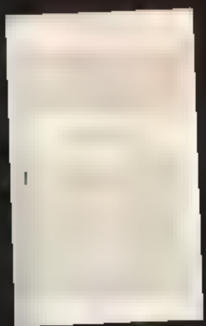
were influenced by Neptune's gravitational pull.

Finally, there is 'Hawking radiation'. Stephen Hawking surprised himself when, in 1974, he realised that black holes couldn't truly be black. The idea came from his understanding of quantum physics – the science governing very small things – and in particular the 'uncertainty principle'. This said that localised energy can fluctuate significantly over small periods of time, allowing pairs of quantum particles to emerge and then disappear again before they are observed. If this happens near a black hole's event horizon, one of these 'virtual' particles could be pulled in while the other flies off. These stray particles make up Hawking radiation. This is unlikely to be detectable at any great distance.

After Schwarzschild's solution, black holes seemed the natural end for the right kind of stars with masses at least three times that of the Sun. But this particular scale is not a limitation of the black hole itself, merely the formation mechanism. In principle, black holes could exist on any scale from the microscopic all the way through to millions of times the mass of the Sun. There are broadly four categories, two of which have probably been detected.

At the tiny, totally hypothetical end of the scale are micro black holes and quantum black holes. A micro black hole would form, for instance, if Earth collapsed, forming an event horizon about 9mm across, though thankfully there is no known mechanism for this to occur. Quantum black holes are even smaller, from a scale of around 5,000 protons up. In principle, they could be produced in a particle accelerator and would almost immediately decay. Current accelerators don't have the energy to produce one unaided, but if the Universe has extra dimensions, this

TIMELINE

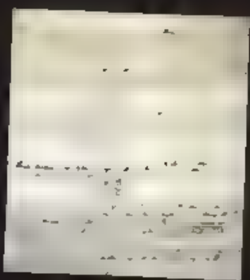


1783

[illegible] is read at the Royal Society. He hoped to deduce the mass of stars from their effect on light and thought a massive-enough star would be able to stop light entirely.

1915

[illegible] publishes his field equations. This set of 10 equations at the heart of General Relativity describe gravity as a curvature of space and time.

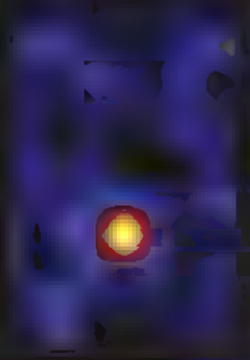


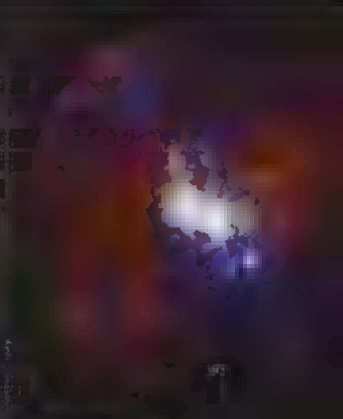
1916

Karl Schwarzschild comes up with his theory, the Schwarzschild radius, which states that if all a body's mass is crammed into a sphere, space-time distortion would be so great that light from the object would never escape.

1971

The first candidate black hole is found. Cygnus X-1 is an X-ray source that was first detected in 1964 and is thought to be a binary star, where material from one star is accelerated into a black hole.





1995

[illegible] (Source 2) is observed by the Max Planck Institute and UCLA. It orbits an apparent supermassive black hole, Sagittarius A*, at the heart of the Milky Way.

could reduce the energy threshold to something accessible.

The best evidence we have for conventional black holes, formed from the collapse of a dying star, is X-ray binaries. In these objects, material is accelerated from one normal star into an invisible star, giving off X-rays. This can happen with a neutron star, but if the 'eating' star has more than about three times the mass of the Sun, it should, in theory, be a black hole.

The first X-ray binary widely recognised as containing a black hole was Cygnus X-1. A powerful X-ray source was detected in 1964 and was identified as a black hole candidate in 1971. A blue supergiant star in the binary was being stripped of material by the X-ray source, which appeared to have a mass in the region of 9 to 15 times that of the Sun. In 1975, Kip Thorne and Stephen Hawking made a bet as to whether this was, indeed, a black hole. Hawking, who was on the 'no' side, paid up in 1990 when better observational data was obtained.

Since 1990, the identification of Cygnus X-1 has become less certain. This is because the companion star is very large, making it difficult to be sure of the mass of its 'compact object' companion. Many other candidates have been detected since, but evidence remains indirect and is based on theoretical assumptions about the maximum size of a neutron star that may not be borne out in practice.

Supermassive black holes are thought to exist at the heart of most galaxies. Such black holes may play a significant role in galaxy formation, giving the galaxy a hub around which to coalesce. Candidate Supermassive black holes have been detected at many galactic centres, thanks to the odd motion of nearby stars and the high electromagnetic emissions from these regions.

A star called S2 orbits the centre of the Milky Way at about four times the radius of the orbit of Neptune. From S2's path, it seems likely it's orbiting something with a mass of about 4.3 million times that of the Sun. The object matches the position of an intense radio source called Sagittarius A* and there is currently no other explanation for this except a supermassive black hole. Elsewhere, stellar destruction gives a clue. Unusually bright light signatures in distant galaxies are thought to be stars being ripped apart by supermassive black holes.

All is not certain, though. A 2014 study suggested that black holes won't form at all. The authors believed that as a star collapses, Hawking radiation would reduce the mass of the star sufficiently that the black hole never reaches completion. There would be an ultra-dense body acting like a black hole, but without the singularity or the event horizon. The paper isn't universally accepted, but illustrates how our understanding of black holes is primarily driven by theory. A theory that was given a significant boost in April 2019 when the first image of the shadow of a black hole was captured by an international team of scientists using the Event Horizon Telescope. **SF**

2012

The best evidence to date of a star being ripped apart by a supermassive black hole is detected by the Pan-STARRS telescope on Hawaii and analysed by a team at Johns Hopkins University

ESO/EHT COLLABORATION, GETTY X2, NASA X3, ESO

by **BRIAN CLEGG**

Brian is a science writer and author. His latest book is Professor Maxwell's Duplicitous Demon

NEED TO KNOW

A handy list of the terminology connected to the study of black holes

ACCRETION DISC

...ation process of a so... ...em). In the case of bl... ...nearby matter is ... ...off a bright...

JET

...emitted at right angles to the accretion disc. The cause ... these jets is uncertain, though they may be the result of a complex magnetic field

PAULI EXCLUSION PRINCIPLE

...is principle of quantum ...chanics establishes that ...ermions (a type of subatomic ...le) cannot be in an ... quantum state. Th... results in 'exchange interaction', which is like a short-range force keeping ...ermions apart – except in extreme conditions such as black hole formation

SINGULARITY

In the case of astrophys... ...gularity is a mathematically predicted condition where ... ...istorted by gravitation tha... ...vity tends t... ...nfinity and current theories

THE END OF THE UNIVERSE

We know the Universe started with the Big Bang, but how will it end? With another bang? Or a will it be a rip, a crunch, a freeze or a bounce instead? *Brian Clegg* gazes into a cosmological crystal ball

Q Will the Universe end soon?

A No need to panic. It won't end for many billions of years. Depending on the scenario, we have between 20 billion and 100 billion billion years left to enjoy our cosmos.

The idea that the Universe can't last forever is based on the second law of thermodynamics, which states that systems have a tendency to degenerate when left to their own devices.

Q How might the Universe end?

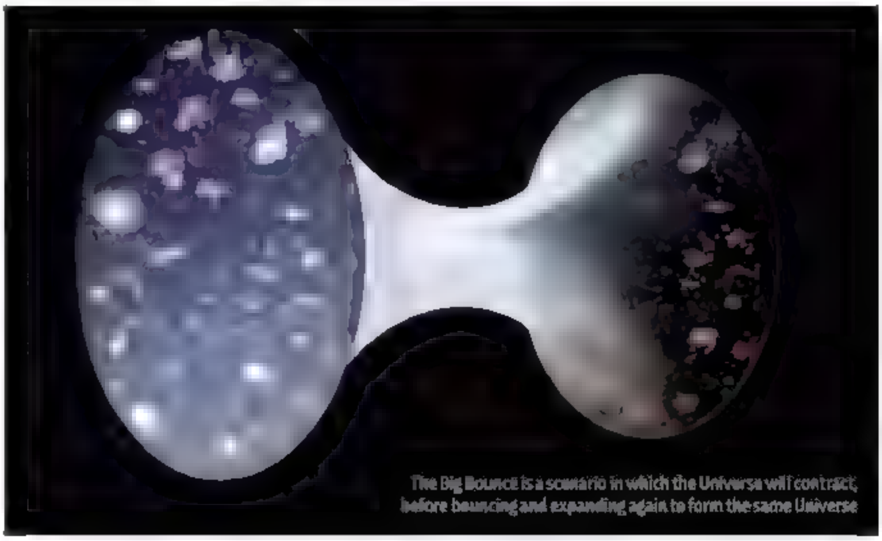
A This is where we enter the realm of cosmological speculation. There are four broad scenarios that have the most support.

Two of these scenarios involve the Universe continuing to expand, getting increasingly thinner and more dispersed. The most conventional scenario, the Big Freeze, is simply the ultimate outcome of standard thermodynamics. Everything evens out until there is absolutely nothing happening in a totally diffuse Universe. The more dramatic version incorporates the observation that the Universe is not just expanding, but that the expansion is accelerating. If this accelerating expansion is extrapolated to the extreme, we get the Big Rip, in which all of the matter in the Universe, from planets and galaxies to fundamental particles and space-time itself, is pulled apart as the expansion heads off to infinity.

By contrast, the other two scenarios see the expansion of the Universe eventually reversing. If everything ends in the Big Crunch, we see a reversal of everything we've experienced to date, returning to an infinitely dense point – a 'singularity'. This can then produce a new Big Bang and a new Universe, giving a possibility for a cycle of universes. In the subtly different Big Bounce, the Universe again reaches a peak size and begins to contract, but in this instance, it never gets as far as a singularity before bouncing and expanding again. The difference from the Big Crunch is that some aspects of the earlier Universe can carry over into the next one. In effect, the Big Crunch generates a new Universe, whereas the Big Bounce sees the same Universe repeatedly expand and contract.

Q What does it depend on?

A All these possibilities are devised by taking the observed behaviour of the Universe and then ●



The Big Bounce is a scenario in which the Universe will contract, before bouncing and expanding again to form the same Universe

SCIENCE PHOTO L BRARY

IN A NUTSHELL

While cosmologists agree that the Universe will end in billions of years' time, what they're undecided on is how it will happen. Currently, there are four scenarios that have the most support: the Big Rip (visualised here), the Big Bounce, the Big Freeze and the Big Crunch.

> "Einstein's General Theory of Relativity can be used to model the entire Universe in a crude fashion"

➋ extrapolating some key aspects of physics into the future, notably the General Theory of Relativity. This theory, Einstein's masterpiece describing the relationship between matter, gravity, space and time, can be used to model the entire Universe in a crude fashion. Of all of the factors involved in predicting the future of the Universe, the existence of the accelerating expansion is the most reliable. The 'extrapolation into the future' part is trickier. We can't experiment with a Universe and try out different scenarios. There's nothing to say that things will continue in the future the way they have in the past. Perhaps most doubtful is the use of General Relativity, as it doesn't work at the level of quantum particles, and using it to model the Universe requires vast simplifications, making the model significantly different from reality.

Q Which theory is the most popular among cosmologists?

A It depends who you ask! The problem with theories like the Big Crunch and the Big Bounce is that models of the Universe suggest that such processes would run out of steam, unable to keep recycling unless there was some external input. The best supported version of the Big Bounce depends on something called 'ekpyrotic theory', a concept based on an unproven advanced version of string theory. According to this picture, our Universe is a four-dimensional 'brane' (three of space, one of time), floating in a space-time continuum and the Big Bounce occurs when two such branes collide, providing that external input.

Variants of the Big Freeze, or 'heat death', in which everything runs out of energy and stars finally stop forming in around 100 billion billion years, were most popular among cosmologists for a long time. Now, though, the Big Rip is probably the best supported theory, because 'dark energy' seems to be driven by the size of the Universe, so the bigger it gets, the more powerful the effect.

HOW WILL THE UNIVERSE END?

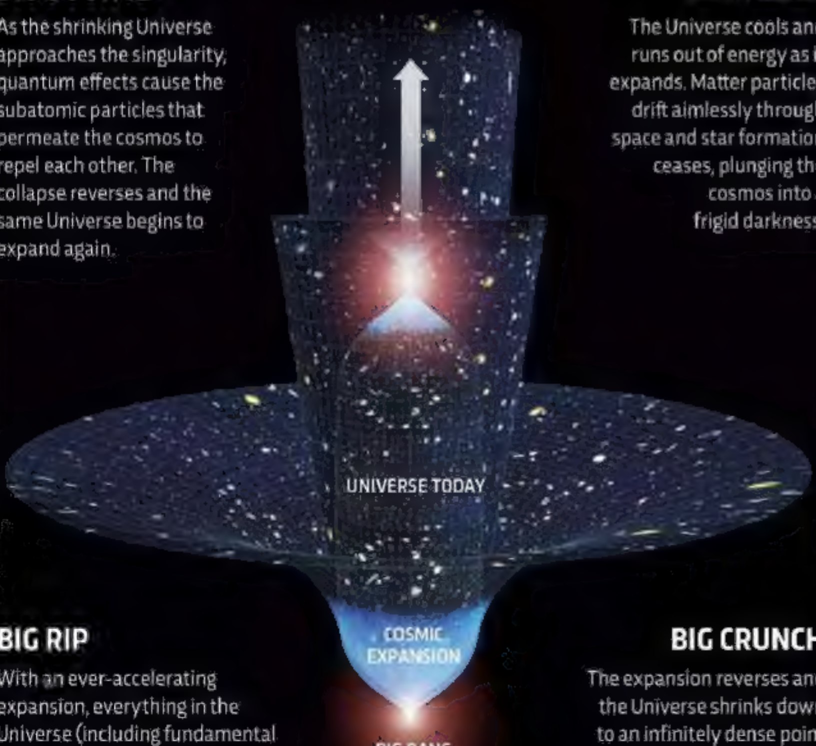
The four most popular scenarios

BIG BOUNCE

As the shrinking Universe approaches the singularity, quantum effects cause the subatomic particles that permeate the cosmos to repel each other. The collapse reverses and the same Universe begins to expand again.

BIG FREEZE

The Universe cools and runs out of energy as it expands. Matter particles drift aimlessly through space and star formation ceases, plunging the cosmos into a frigid darkness.



BIG RIP

With an ever-accelerating expansion, everything in the Universe (including fundamental particles) rip themselves apart, giving off vast amounts of light. In the extreme, space-time itself disintegrates.

BIG CRUNCH

The expansion reverses and the Universe shrinks down to an infinitely dense point – a singularity – where all physics as we know it breaks down, triggering a new Big Bang.

Q What is dark energy?

A No one knows exactly what dark energy is, but it causes the acceleration of the expansion of the Universe. Without dark energy, General Relativity models predict different final outcomes. It might be a fundamental property of empty space, or it might be a new kind of energy field or fundamental force, filling all of space but having the opposite effects to normal energy and matter. Finally, it might be that Einstein's theory of gravity is incorrect, and that a new theory is needed. The person who solves this mystery will be an instant Nobel Prize winner.

Q Will another universe be born after this one dies?

A If either the Big Crunch or Big Bounce happens, definitely. But even the more likely ever-expanding options don't mean the end of everything. Most cosmologists believe that this Universe is one of many in a larger 'multiverse', with Big Bangs happening regularly. **SF**

by **BRIAN CLEGG** (@brianclegg)
Brian is a science writer and author. His latest book is Professor Maxwell's Duplicitous Demon.

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the science of good bone structure
You may think bone is solid or fixed. In fact it is living tissue, in constant change. To keep bones healthy you must have the right nutrients in your daily diet.
Calcium is essential to help maintain normal bones, as is vitamin D, which is necessary for the normal absorption and utilisation of calcium. But did you realise magnesium and zinc are important for bones too? Both men and women need to look after their bones throughout their life, and remember it's never too early or too late to start a bone-friendly way of life!
FIZZ
Makes a tasty drink.
A convenient, refreshing orange flavoured effervescent drink.
Osteocare FIZZ
Healthy tip:
Leafy greens contain minerals such as magnesium and calcium
Osteocare ORIGINAL
calcium magnesium vitamin D (10µg) & zinc
bones
ORIGINAL
More than just calcium.
Provides calcium carefully balanced with vitamin D, zinc and magnesium which all contribute to the maintenance of normal bones.
Healthy tip:
Sardines contain high levels of vitamin D & calcium
Osteocare LIQUID ORIGINAL
calcium magnesium vitamin D, zinc
bones
LIQUID
Excellent taste.
Ideal for children or those who have difficulty swallowing tablets.
Available in 200ml and 500ml.
Healthy tip:
Almonds are a great source of magnesium and zinc
Osteocare CHEWABLE
calcium magnesium vitamin D, zinc
bones
CHEWABLE
Easy to take.
Provides the original formula in a great tasting peppermint and orange flavoured chewable tablet.
*UK's No.1 bone health supplement brand. Source: Nielsen GB ScanTrack Total Coverage Unit Retail Sales 52 w/e 18 May 2019. To verify contact Vitabiotics Ltd, 1 Apsley Way, London NW2 7HF.
From Boots, Superdrug, Holland & Barrett, supermarkets, chemists, health stores & www.osteocare.com
Osteocare® supports
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Better bone health for everybody
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VITABIOTICS

Take a tour of the most incredible phenomena in the Universe, from the Big Bang to the Big Bounce – and everything in between.

Written by experts, this Special Edition clearly explains the fundamental ideas in science from general relativity to quantum physics. It reveals how we came to comprehend black holes, determine the speed of light and discover the structure of DNA. It discusses the biggest genetic breakthroughs from GM babies to the creation of synthetic life. And it tells the story of the hunt for the greatest enigma in the cosmos: dark matter.

FROM THE MAKERS OF ***BBC SCIENCE FOCUS*** MAGAZINE